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A REVIEW OF RESEARCH AND DEVELOPMENT IN CRASH-WORTHINESS OF GENERAL AVIATION AIRCRAFT: SEATS, RESTRAINTS AND FLOOR STRUCTURES

by

P. Huculak

National Aeronautical Establishment

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A REVIEW OF RESEARCH AND DEVELOPMENT IN CRASHWORTHINESS OF GENERAL AVIATION AIRCRAFT: SEATS, RESTRAINTS AND FLOOR STRUCTURES

REVUE DE LA RECHERCHE ET DU DÉVELOPPEMENT EN MATIÈRE DE RÉSISTANCE À L'ÉCRASEMENT DES AÉRONEFS D'AVIATION GÉNÉRALE: SONT EXAMINÉS LES SIÈGES, LES ATTACHES ET LES PLANCHERS

by/par

P. Huculak

National Aeronautical Establishment/
Établissement national d'aéronautique

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W. Wallace, Head/Chef
Structures and Materials Laboratory/
Laboratoire des structures et matériaux

G.F. Marsters
Director/directeur

ABSTRACT

A literature search has been conduted to determine the status of knowledge of the crashworthiness aspects of general aviation aircraft. Research and development work relating to seats, restraints, and floor structures of general aviation aircraft has been selected for review.

The primary goal of crashworthiness studies has been the reduction of fatal and serious accidents. Study of the work on seats, restraints and floor structures has revealed that more attention to several research topics could ameliorate high accident rates in general aviation.

RÉSUMÉ

Une recherche documentaire a été effectuée afin de déterminer l'état de nos connaissances sur les aspects de la résistance à l'écrasement des aéronefs d'aviation générale. La recherche et le travail de développement portant sur les sièges, les attaches et les structures de plancher des aéronefs d'aviation générale ont été examinés.

Les études de résistance à l'écrasement visent principalement la réduction du nombre d'accidents graves ou mortels. L'examen du travail consacré aux sièges, aux attaches et aux structures de plancher montre qu'une attention plus grande envers plusieurs sujets de recherche pourrait faire baisser le taux élevé des accidents dans l'aviation générale.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

LIST OF TABLES

LIST OF FIGURES

TABLE OF CONTENTS (Cont'd)

LIST OF FIGURES (Cont'd)

TABLE OF CONTENTS (Cont'd)

LIST OF FIGURES (Cont'd)

APPENDICES

1.0 Introduction

A literature search has been conducted to define the status of research and development on crashworthiness in general aviation (G.A.) seats, restraints and floor structures. The nature of much of the work in G.A. crashworthiness investigations is now of a systems approach featuring information obtained from accident reconstruction, human injury criteria and tolerance limits, human and surrogate modelling, and full-scale aircraft and component impact testing.

Aircraft accident investigations now focus on the crash injury aspects of survivability in order to increase the survival rate even though accident prevention will continue to be a priority. The U.S. Army Crash Survival Design Guide(1) defined a survivable accident as one "in which the forces transmitted to the occupant through the seat and restraint system do not exceed the limits of human tolerance to abrupt accelerations and in which the structure in the occupant's immediate environment remains substantially intact to the extent that a livable volume is provided throughout the crash sequence".

Monroe and McLeish of Sypher:Mueller(2) provided an overview of the research and development in G.A. crashworthiness in Canada and the United States (U.S.). They emphasized Canada-U.S. agreements and possible joint participation. The major institutions involved were also identified. Crashworthiness Regulations of the U.S. Federal Aviation Administration (FAA), both past and present, were discussed. The impact of these regulations on the Canadian G.A. aircraft industry was emphasized. Research activities of the FAA and the U.S. National Transportation and Safety Board (NTSB) were discussed. Six areas in G.A. crashworthiness were identified for further research and development. They were: 1) computer simulation/modelling of existing crash dynamics data, 2) systems approach and coordination of research, 3) retrofit of existing G.A. aircraft, 4) composite structures, 5) post-crash survival, and 6) fuel systems.

Recommendations were also made regarding a Canadian R&D program and the institutions that could be involved in such a program.

Proceedings of a seminar on G.A. R&D held in Ottawa(3) reviewed the status of North American research and development in G.A. crashworthiness and covered Canada's possible future role in crashworthiness activities.

This report presents a survey of R&D activities in G.A. crashworthiness relating to seats, restraints and floor structures. Other associated topics (accident statistics, human injury and tolerance, impact testing and modelling) are included to provide background

information. Some recommendations are made regarding Canadian participation in G.A. crashworthiness research and development.

2.0 General Aviation Accidents and Operations

Accident investigators gather data in order to determine the adequacy of the crashworthiness of aircraft. The factors usually considered are: 1) aircraft crash pulse (i.e. velocity at impact, aircraft attitude and time duration involved), 2) structural damage, 3) forces necessary to cause the damage, 4) injuries, and 5) causes of injuries.

Accident data is usually subdivided into categories according to the amount and completeness of available information. Detailed analysis is usually restricted to a select group of accidents for which comprehensive documentation is available.

Hasbrook(4), one of the first aircraft accident investigators to study crashworthiness, studied survivable crashes in G.A. aircraft. He reconstructed the crash load vectors to ascertain their effects on the occupants.

Bergey(5) conducted a study of G.A. accidents occurring during the 1964 to 1967 period in order to identify specific aircraft crashworthiness characteristics that reduced occupant fatalities. None were identifiable. Analysis of the 1114 accidents revealed that fatality rates for individual aircraft models differed by a factor of three. Table 1 presents the ratio of fatal accidents to total accidents for 30 aircraft models(5) It was found that the faster aircraft had higher accident rates with only a few exceptions. It was also found that the aluminum semi-monologue airframes had a fatality rate that was 17% lower than those of either steel tube or steel tube/aluminum construction.

Snyder provided a history of crashworthiness developments in G.A. going back to 1910(6). He listed accident statistics and the early sources for these. The fatality rate in G.A. aircraft was 3.5 times greater than that of the automobile and 154 times greater than scheduled air travel in 1973. These results were based on passenger-miles travelled.

Tennyson et al.(7) studied Canadian aircraft accident statistics with emphasis on fuselage damage involved. They compared G.A. accidents with the transport category accidents. It was shown that for the period 1969 to 1974, total casualties for Canadian fixed wing aircraft were considerably higher (based on number of flying hours) than those in the U.S.

Snyder(8) showed the trends in U.S. G.A. accidents and fatalities for the years 1960 to 1977. There was a decrease in the number of accidents reported (due largely to a change in

methodology) since 1967, but no attendant decrease in the number of fatalities. These results are shown in Fig. 1[8].

Clark of NTSB[9] reported on a large accident investigation study involving 36,500 G.A. aircraft and over 76,000 occupants (16% killed, 9% seriously injured) for the 1972-1981 period. In a more detailed study concerning survivability of about 1200 occupants in over 500 accidents, Clark and his associates at NTSB found:

1) a 20% reduction in fatalities by use of shoulder harnesses,
2) that 88% of severely injured would have had significantly reduced injuries with shoulder harness usage,
3) energy absorbing seat installations would reduce injuries of 34% of the seriously injured category,
4) there would be only a 2% reduction in fatalities with energy absorbing seat installations,
5) that 27% of the seats failed in survivable accidents, and
6) that the effective harness usage rate was only 16%. (40% of the seats were equipped with harnesses and only 40% of these were used).

An envelope of survivability was established relating velocity of impact as a function of impact angle. These limits are essentially 45 knots at 90°, 60 knots at 45° and 75 knots at 0°. The survivability envelope is shown in Figure 2[9].

Clark also reported on the detailed investigation of 39 survivable accidents. Structural deformations, impact parameters and injury states were ascertained. Peak decelerations and impact velocity changes were then calculated.[9]

Wittlin provided an extensive review of the G.A. aircraft usage in the U.S.[10]. Table 2 lists the G.A. aircraft configurations in relation to maximum takeoff weight and usage[10]. Table 3 gives the performance characteristics (stall speed, cruise speed and occupant capacity) for the various configurations[10].

Aircraft construction features are important in considerations of crashworthiness. Cabin reinforcement, seat and restraint retrofit and attachment point improvements require extensive knowledge of the structural design of the aircraft. Table 4 lists the wing, fuselage, engine attachment, landing gear and tail unit structural features for four G.A. weight categories[10] (agricultural category included). The operational velocity/weight envelope of G.A. aircraft is presented in Figure 3[10].

G.A. aircraft accidents entail stalls, ground collisions and obstacle collisions. Wittlin[11] has shown that these accidents occur on flat terrain (40% of the time), on rolling terrain (22%), in mountainous terrain (11%), on hills (8%), in dense trees (9%) and at airports (2%).

3.0 Human Injury and Injury Tolerance

In an aircraft crash the deceleration is characterized by forces of less than 0.2 seconds duration. Secondary impacts may involve the occupant with cabin structure and other objects. Human impact tolerance depends on: 1) direction of impact, 2) type of loading, 3) type of restraint system used, 4) age, sex and physical condition of person, and 5) part of body involved. Tolerance data is obtained from human surrogates such as animals or cadavers, from voluntary exposure, from falls, and from accident investigations.

The Abbreviated Injury Scale (AIS) on a scale from 0 to 6 describes the severity of injury. Forces and moments result in injury but are difficult to measure and therefore decelerations or G-levels (acceleration or deceleration levels expressed as multiples of the gravitational acceleration) are normally the principal measures of tolerance.

3.1 Head Injuries and Tolerances

The majority of severe or fatal injuries in G.A. crashes involve the head. Head injuries are due to direct impact and only rarely - pure deceleration forces. Impact severity depends on the shape and hardness of the impactor. Reference 12 is a good source for this information and is periodically updated.

The brain injury mechanisms are more complex and involve: 1) shear failure, 2) direct pressure build-up, and 3) cavitation damage. The mechanisms are discussed in Reference 13.

Lissner[14] derived the head impact tolerance curve which became known as the Wayne State Tolerance Curve for impact against surfaces. It is shown in Figure 4[12] where the effective acceleration refers to the front-to-back average acceleration at the occipital bone.

The Gadd Severity Index (GSI)[15] was derived in the following way

$$GSI = \int_0^T a^n dt \langle 1000$$

where a = | average acceleration |

n = 2.5 (slope of Wayne State Curve)

T = duration of impact

The Head Injury Criteria (HIC)[16] replaced the GIS in 1972. It was defined as

$$\mathrm{HIC} = (T_1 - T_2)\left[\frac{1}{T_2 - T_1}\int_{T_1}^{T_2} a\,dt\right]^n_{\text{maximum value}}$$

where T_1, T_2 are integration limits (variable)

n and a as defined above.

Shortcomings in the HIC have led to the possible adoption of the Mean Strain Criterion (MSC) put forth by Stalnaker et al.[17].

3.2 Spine and Neck Injuries and Tolerances

Spine and neck injuries can be very complex and are usually associated with several forces and moments acting simultaneously. Also, body posture, type of seat and restraint system are important factors in determining injury type and severity. King[18] provided a concise literature review to 1975 on spine injury research relating to aircraft crashworthiness.

Eiband[19] established the 20-G (for 200 msec.) tolerance limit for parallel to the spine (headward) impact for well-restrained occupants. The 20-G value has been used for ejection seat design. The transverse frontal impact tolerance value was established at greater than 40G[20]. There is insufficient information for the combined vertical and frontal impact case. The lateral impact limit is about 8 to 10 G as proposed by Zaborowski et al.[21] and Patrick et al.[22]. Ewing[23] presented a summary of work on injuries to the restrained and unrestrained neck. The more severe injuries occur when the head is free to whip. Cheng et al. [24] derived neck load limits in an unrestrained frontal crash as: a 6 kN tensile force and a 340 Nm moment.

The Dynamic Response Index (DRI) was developed to represent the dynamic compression of the human spine to upward (headward) loading[25]. The spinal injury rate is shown in Figure 5[26] as a function of the DRI. The DRI correlated very strongly with airspeed at ejection rising from a value of 12 at 100 knots air speed to a value of 23 at 550 knots.

3.3 Chest Injuries and Tolerances

The major dangers associated with chest injury are:(27)

1) excessive rib fractures leading to collapse of the thorax cavity,
2) lung puncture, and

3) heart and aorta damage.

The measures used to quantify thorax tolerance have been chest deflection, spinal accelcration and sternal velocity and acceleration.

3.4 Recent Research in Modelling Human Response

Coltman[28] of Simula Inc., Tempe, Arizona, reported a major study sponsored by the U.S. Army and the FAA to improve the crashworthiness of U.S. Army helicopters. At the beginning of the study it was considered that there was insufficient information on human tolerance to headward, parallel to the spine deceleration. (The previous significant program to address the problem of parallel to the spine aircraft occupant response was carried out in 1969/70 by the U.S. Army[29]).

Sixty-two cadaver and dummy crash tests were carried out at four organizations to obtain data relating to seat and occupant dynamics. Energy absorbing and rigid seats were employed to study the effect of thirteen variables. The condition of the spine was investigated after each test in order to determine human tolerance to vertical decelerations. Peak decelerations, body segment compression and DRI values were obtained from the SOM/LA occupant model values of deceleration[30].

The study concluded: 1) that the forces and moments acting on the spine provide a means of correlating test performance with spinal injury, 2) that there was some uncertainty in the response of the spine of the Part 572 dummy[31]. (The 77 kg weight, 50th percentile male anthropomorphic dummy is an industry standard and provides a level of repeatability in impact testing unattainable with other dummies. Use of the 77 kg design weight results in the most injury protection for the widest range of occupant weights. The reinforced rubber cylinder of the spine of the Part 572 dummy permits easier positioning during tests than is possible with other dummies).

The most recent work on human dynamic response by the U.S. Air Force was reported by von Gierke et al.[32]. The study focused on whole body tolerance to impact, modelling human response and the development of the Advanced Dynamic Anthropomorphic Manikin (ADAM) dummy.

The idealization of human response as being that of a mass supported by a spring and dampers, which formed the basis of the DRI, was extended to a six-degree-of-freedom characterization. Besides the three orthogonal axes, rotational tolerances were also added. The combined hazard limits were then represented in the form of an ellipsoidal envelope. In

Figure 6[32] the derived response was adjusted to conform to the results of deceleration tests in which cardiovascular shock (filled symbols) and spinal fractures (open symbols) had occurred.

4.0 Crash Testing and Crash Modelling

Simulated crashes with full-scale or scale model aircraft are conducted to study impact parameters and the extent of structural failure. Further work on seats, restraints, cabin interiors and evaluation of energy absorbing elements such as subfloors then follows. Impact reconstruction involves the determination of crash imprint, crash angle, velocity of impact, crash pulse duration and shape, and the forces involved. Crash data is employed to develop analytical models of the whole aircraft or subcomponents such as fuselage sections, floors or seats.

Scale model crash impact tests have serious short-comings because geometric scale effects at high strain rates are not well defined. Jones[33] listed several instances of the inadequacy of geometric scaling laws as applied to dynamic tearing, cutting or crack growth. (It has been established, for example that a large structure can crack before yielding whereas a small coupon of the same material could yield before fracture).

4.1 Tests and Test Facilities

The National Advisory Committee for Aeronautics (NACA) initiated full-scale aircraft crash testing in the 1950's[34,35]. Aircraft were accelerated along a horizontal guide rail to impact a barrier.

A joint NASA/FAA crash test program in general aviation was begun in 1973 to study crashworthiness in survivable accidents[36]. Full-scale crash tests were conducted to determine the response of occupants, seats, restraints and aircraft structures. Impact parameters relating loads to structural damage and loads directed on the occupants were also studied. Alfaro-Bou and Vaughan[37] described the crash testing of two G.A. aircraft in the series. Figure 7[37] shows the aircraft release system for a guided crash test.

Alfaro-Bou et al[38] crashed twelve G.A. aircraft at NASA Langley to obtain the resulting crash pulse characteristics. All but one, which was crashed on soil, were crashed on concrete at impact velocities of 23 to 41 m/sec. External ground cameras determined the dynamic response of the aircraft from the impact attitude, velocity, displacements and deformations. Slap-down (rotation of the aircraft about the impact point) on concrete contributed to an increase in the deceleration pulses. Analysis showed that each crash characterized by the particular airframe and impact conditions had a unique crash pulse.

Thomson and Caiafa[39] also described the NASA/FAA crash test program. Use of a finite element non-linear computer program, DYCAST, and modelling of seats and subfloor structure was described.

UTIAS[40] has been involved in crash testing and modelling of fuselage structures. The crash testing has been carried out mainly for corroboration of their dynamic structural analysis. The group has concluded that extensive computer analyses are necessary because the costs of full-scale aircraft tests are prohibitive.

Wittlin[41] briefly outlined aircraft crash dynamics research carried out in the 1980's including work on G.A. aircraft.

Sarrailhe[42] reported on the Australian crash safety program at ARL. They carried out drop tests on light aircraft cabins. The impact pulse reached 15 G for a velocity change of 4.5 m/sec.

Wittlin[43] studied aircraft crash pulses in relation to airframe design. A procedure was developed to evaluate crash pulse shapes with regard to their severity. An attempt was made to obtain equivalence between dynamic and static tests. For a simple single degree-of-freedom system defined by mass, stiffness and damping, standard input-output relationships can be derived and static-dynamic equivalences are possible provided failure modes are identical.

4.2 Dynamic Models

Aircraft crash tests are expensive and usually replaced or at least complemented with numerical calculation. Dynamic analysis is required for impact modelling because the rise time of loading is usually of the same duration as the period of ensuing local deformations. A quasi-static analysis will underestimate the magnitude of such deformations.

4.2.1 Structural Models

Numerical codes for impact analysis generally employ time integration algorithms with either fixed (explicit) or variable (implicit) time steps. Much work has been carried out to handle nonlinearities, incremental plasticity and displacement and various constitutive material relationships. Many programs are available including KRASH[44] in many versions and DYCAST[45]. KRASH is essentially a hybrid modelling technique that idealizes structures as a series of light beams connecting rigid lumped masses. It requires experimentation to obtain the nonlinear stiffness behaviour of component beams. A KRASH model of a G.A.

aircraft is shown in Figure 8[43].

Program VEDYAC was developed at the University of Milano and uses fixed time steps and can simulate body contact and contact forces[46]. VEDYAC can also model motion of anthropomorphic dummy models.

Other finite element codes for structures are CRASHMAS, and DYSMAS[46].

4.2.2 Seat and Occupant Models

It is necessary to model gross human dynamics in order to obtain positional information and to study the interactions of occupants, seats and the restraint systems. The mathematical models supplement work on human response and injury criteria. Separate human response models have been developed to establish injury criteria and were considered in Section 3.4.

A number of dynamic models of the human body have been developed for crashworthiness research[47,48,49,50]. One of the more versatile and comprehensive models called SOM/LA also incorporates seat interactions[51]. It is shown in Figure 9 and incorporates twelve rigid links, six ball and socket joints, and five hinge joints for a total of 29 degrees of freedom for three dimensional motion[52]. The plane-motion SOM/LA model is shown in Figure 10 and is used for lap belt or symmetric upper torso restraint description. The seat is characterized by conventional finite-elements consisting of beam and triangular elements (see Figure 11[51]). Model optimization was based on predicting head acceleration and injury severity index within $\pm 5\%$ of the mean of measured data.

More recent work on SOM/LA[52] entailed the computation of segment penetration into cushions or floor surfaces. A subroutine checks for ellipsoidal surface contact and contact forces are calculated. Figure 12[52] shows occupant response to impact of chest and legs employing only a lap belt as a restraint. Other features of the model include: 1) the option of using, two, three and five point restraint systems, 2) joints modelled as nonlinear torsion springs with viscous damping, 3) capability to model frontal, vertical and lateral impacts, 4) ability to simulate either a human or an anthropomorphic dummy, and 5) accurate modelling of restraint forces to include the elongation characteristics of restraint webbing.

Validation of the seat-occupant model SOM/LA was described in Reference 53.

Other models of the human include the ATB model developed by Calspan Corporation, the MADYMO model developed by the Netherlands[54] and the HSM model developed by Belitshko and Privitzer[55]. A summary of the characteristics of the human models and some of the structural models is given in Table 5[46].

5.0 General Aviation Aircraft Seats

There has been general agreement among crashworthiness researchers that the seat and restraint system are the primary features of occupant protection in crashes. Accident investigations and full-scale crash tests have shown that seat attachment strengths were lower than occupant inertia loads in survivable impacts[56].

The design of crashworthy seats was initiated in the mid 1960's during work on military helicopters. Difficulties were encountered in maintaining the stroking capability at different impact angles. The distortion of the attachment points and mounting structure complicated seat design.

A crashworthy seat must withstand crash impulse loads and attenuate occupant accelerations. The peak-G loading can be reduced and the energy of the pulse is transferred to the longer duration stroking of the seat.

Research attention focused on seats to attenuate vertical accelerations after padded instrument panels, lap belts and shoulder belts had been introduced. Some of the early work was carried out by Pesman[57] and some design criteria were established by Turnbow et al.[58].

Rothe et al[59] introduced the concept of a permanently deformable massless cushion as an energy absorbing element located between the bottom of the seat and the floor. This cushion could be energy absorbing elements, honeycomb materials or special foams. Idealized responses of floor and occupant are shown in Figure 13,[59], where G_m is the deceleration design value at which stroking of the seat begins (typically at about 12 G). The relationship shown in Figure 14[59] was developed to obtain the required seat cushion thickness H as a function of impact velocity V_i, gravitational acceleration g, amount of aircraft deformation D_s, and maximum usable strain ε_m in the energy absorber. An example of a material stress-strain curve used to derive the maximum strain is also shown in Figure 14. HUP-2 helicopter drop tests confirmed the relationship for H.

Vulcan et al.[60] initiated a research program on energy absorbing cushions because of the occurrence of spinal injuries in G.A. and glider aircraft. A seat cushion was designed to reduce spinal injuries by attenutating vertical crash forces. The approach was suitable for retrofit protection where sufficient space was available for the over-sized cushion. The authors tested six cushions of varying construction. The material types were: 1) flock-filled, type F, 2) soft 50 mm thick polyurethane foam, type U, 3) firm polyester-based polyurethane foam of 125 mm thickness, type S, 4) composite of firm polyurethane foam and paper honeycomb, type H, 5) firm polyurethane of 125 mm thickness, type G, and 6) a rigid polyurethane foam, type K. Crash tests were carried out and some of the carriage (floor) and

body block acceleration pulses are shown in Figure15[60] for four of the six cushions. Allowable impact velocities were limited to rather low values for all of the cushions tested because of the restricted stroke range.

The S-leg seat was introduced by Underhill[61] and shown in Figure 16. The design requirement called for protection in a 7.62 m/sec. vertical impact, taking place in 203 mm. The crash tests showed that the S-leg seat attenuated 40-G carriage deceleration to about 22 G at the pelvic location of a 91 kg dummy.

Desjardins and Singley[62] outlined how seats designed by static analysis either failed in a crash test or resulted in too high a G-loading on the occupant. The static criteria were those of the Crash Survival Design Guide[58].

Warrick and Desjardins[63] of Simula Inc. reported on the conceptualization and prototype testing of two under seat energy absorbers for use in nonadjustable G.A. seats. One concept consisted of an inflated air bag and the other was a convoluted sheet-metal bellows. Simplicity of design employing ordinary materials and fabrication techniques were goals of the program. The 95th percentile crash pulse established for light fixed-wing aircraft by the Crash Survival Design Guide[58] served as the design requirement.

In 1979 Reilly and Tanner[64] of Boeing Vertol described work performed under a contract awarded by NASA Langley to design two crashworthy passenger seat concepts suitable for G.A. aircraft. The first concept was the suspended seat, the second being a floor mounted one. Crash Survival Design Guide[58] impulse data was used (forward impact at 15 m/sec. and a 3-axis vertical impact at 15 m/sec.). Ceiling suspension enables seats to be inherently stable during stroking with no need for guides or tracks. Individual energy absorbing elements were tested but functional seats were not.

Kirkham et al[65] reviewed forty-seven survivable or partially survivable G.A. accidents. Table 6 gives the distribution of seat failures in the forty-seven accidents. Seats failed by sliding forward on the track, and by detaching from the track. Legs broke, seat pans and backs failed. There was a gradation of seat failures decreasing from aircraft front to back. Table 7 lists the contribution of seats to injury, i.e. more than would be expected from impact alone. In 30% of the accidents, seat failures contributed to injury severity.

Williams and Fasanella[66] reported on the testing of two seats with S-shaped legs and one foam-cushion seat. The seats were designed as possible retrofits in a fleet of greater than 100 G.A. Cessna aircraft. Dynamic drop tests were carried out at an impact velocity of 10.7 m/sec. at various pitch attitudes. The nominal vertical input acceleration was 20 G with a total pulse duration of 0.088 sec. Pulse shape was approximately trapezoidal with an onset rate of 1800 G/sec. Table 8[66] gives the longitudinal (L) and vertical (N) accelerations (G) as well as the

pulse durations (ΔT). Pelvis values refer to those of the Part 572 anthropomorphic dummy[31]. The S-shaped legs (seat tests 1, 2 and 5) were too massive and underwent very little plastic deformation during stroking. The foam of the cushion seat (tests 3 and 4) was too dense and also resulted in insufficient attenuation of the seat pan and pelvis accelerations. It was recommended that seats be redesigned to stroke at the 12-G level.

Soltis and Olcott[67] outlined the considerations leading to the FAA FAR 23 regulations[68] requiring dynamic testing of seats for G.A. aircraft. Initially a technical working group was formed to review existing research, to develop designs relevant to dynamic crash conditions and to form recommendations for the new regulations. The following formed the basis for the General Aviation Safety Panel's (GASP) work: 1) MIL STD-1290[69], 2) U.S. Army Crash Survival Design Guide[70], 3) U.S. Army crashworthiness work on helicopters, 4) NTSB data files, and 5) FAA/NASA full-scale aircraft controlled impact test program. The panel reviewed the work of Reference 71 and selected a triangular shape for both the longitudinal and vertical crash pulses as best representing NASA crash data. A pulse duration of 0.10 seconds was selected[72]. The impact velocities (12.8 m/sec. longitudinal and 9.5 m/sec. vertical) were chosen on the basis of survivable accident limits discussed in references 71, 73 and 74. Shoulder belt criteria were based on the work reported by Foret-Bruno et al[75]. The pelvic load criteria were derived from the spinal injury work of Coltman[28] and Chandler[76]. The head injury criteria (HIC) employed is the most widely used in crashworthiness and is included in the Federal Motor Vehicle Safety Standard (FMVSS)[77].

Appendix A contains the text of the GASP recommendations[67]. The GASP proposals were incorporated into FAR 23[68]. The excerpts relating to dynamic testing of seats are given in Appendix B.

Canadian Defence and Civil Institute of Environmental Medicine (DCIEM) requested Bell-Helicopter Textron Inc. (BHTI) to investigate energy absorbing crew seat concepts for the CH-136 helicopter. Three candidate energy absorbing crew seats were evaluated by BHTI for DCIEM: 1) a pivoting seat pan, 2) a tension seat, and 3) a guided armored bucket. The most promising one consisted of a wire-deforming energy absorber incorporated in the pivoting seat pan. A limitation of 125 mm in the seat stroking distance was imposed on the design. Fox[78] and Waterhouse and Chowdhury[79] described some of this work.

Hearon and Brinkley[80] tested conventional polyurethane (51 mm thick) and special rate-dependent temperature sensitive polyurethane foams employing human subjects in drop tests. The crash pulses were characterized by: 1) 10 G deceleration peaks, 2) velocity changes of 8 m/sec, and 3) a time to peak G of 58 msec. It was shown that conventional foams of small thickness (51 mm) are only useful for comfort and attenuating low energy, high frequency impacts[81]. The special rate-dependent foams did provide some impact protection.

Colangelo and Russell[82] investigated the role of seats in relation to the type and frequency of injuries and fatalities in G.A. accidents. A data base of 55 accidents for the 1981-1986 period was selected and the frequency of seat failure occurrence was found to be:

1) seat detached and caused restraint system failure (19%)
2) seat detached only (54%)
3) back of seat impactor (21%)
4) seat failed to protect occupant from intrusion by other objects (6%)

The authors concluded that restraint anchor points should not necessarily be attached to the seat; that seat failure alone did not correlate with seat induced injury. It was also concluded that seats: added to injury in 10% of the cases, lessened injury in 8% of the cases and that seats made no difference in the remainder.

6.0 General Aviation Aircraft Restraints

The installation of lap belts and shoulder harnesses in aircraft began in World War I. Beech Aircraft included shoulder harnesses in their G.A. aircraft in the 1950's. The manufacturer stopped installations except on special request because of very poor consumer response. Shoulder harness use is limited at the present time (about 16% of occupants use a shoulder harness). Some tolerance limits associated with seat belt usage in aircraft were estimated to be: 1) 17 G for 0.26 sec.[83], 2) 15 G[57], and 3) 10-20 G[84]. An AvCIR study in 1961 suggested that 25 G was a practical design limit for seat belts[85].

Figure 17[59] shows estimates of how the restraint system affects the impact crash pulse (0.001 to 0.10 sec. duration in frontal impact). These estimates were made before energy absorbing seats were introduced.

Twenty-two dynamic tests were carried out on G.A. occupant restraints (lap belts and lap belt/shoulder harnesses) by Daiutolo[86]. It was shown on the basis of anthropomorphic dummy deceleration records that the restraint systems performed at force levels that were higher than the existing FAA regulatory requirements. The study showed: 1) shortcomings in the lap belt-only restraints resulting in serious to fatal head impacts, 2) lap belt/shoulder harness restraints of the type available as optional equipment provided protection at high force levels, 3) retrofit of restraints could present difficulties in the case of low wing fuselage G.A. aircraft.

The Crash Survival Design Guide[58] (U.S. Army) has information on the design and testing of occupant restraints for light fixed- and rotary-wing aircraft.

Discussion of restraint system criteria and research on restraint systems to 1972 is

contained in Reference 87.

Morgan[88] reviewed the different types of restraint systems available in 1973. Figure 18 and 19 illustrate the ones typically used in G.A.[88].

Walhout[89] of NTSB used accident data to compare shoulder belt usage in aerial application aircraft and in G.A. aircraft for the 1964-1973 period. The results for old and new generation aerial application aircraft are shown in Table 9 and Table 10[89]. The reduction of fatalities in the new generation aircraft was attributed to better designed crash-proof cabins, some being designed to the 25-40 G level. The fatalities in the aerial application and G.A. aircraft for the 1964-1973 period are shown in Figure 20[89].

Carr and Singley[90] studied the design of restraint systems and showed (Figure 21), that the head severity index using dynamic web properties was lower than that of the static ones. Figure 22[90] shows that the lowest head severity index was obtained with 75 mm wide polyester webbing, this being the stiffest system analyzed. The authors rule out energy-absorbing webbing for restraints because: "it requires considerable room to stroke; and after stroking, the occupant has little restraint left for secondary impact pulses during the crash". The authors also recommended the negative-g strap to counteract submarining of the occupant. They found that 60 mm wide webbing was better than 43 mm or 75 mm webbing. (43 mm tends to rope while 75 mm tends to crease).

Sarrailhe and Hearn of ARL[91] conducted energy absorbing seat and yielding restraint tests at the HyGe facility (GM Holden). They measured belt restraint loads at various levels of belt slack. Figure 23[91] shows the load-extension characteristics of the webbing material employed. They indicated that occupant kinetic energy can be absorbed by the restraint system. (The then current design philosophy was to use minimum elongation restraints). The authors appeared to favour yielding or deforming belt systems.

Snyder[92] has collected results of tests conducted on human subjects restrained by 76 mm wide nylon lap belts for forward, rearward and sideward-facing decelerations. Table 11[92]) gives the occupant response as related to peak G levels, deceleration rate and duration time.

Eppinger[93] derived an equation that calculates thoracic fractures (ribs, sternum, clavicle) in terms of shoulder belt load, cadaver weight and age. He predicted that a 5.8 to 6.7 kN upper torso webbing restraint force would result in the minimum number of fractures in a 13.4 m/sec. frontal crash.

Nelson[94] provided a summary of work on restraint systems to 1977.

Sarrailhe[95] of ARL carried out static tests on the cabins and restraint systems of 3

types of G.A. aircraft (designated as A, B and C). "It was found that most of the restraint components were much stronger than the 9 G requirement and it was considered that only minor improvements would be required to ensure 25 G capability (including shoulder belt attachments)". Seats were not as strong as the restraints. Figure 24 and 25[95] show the seat and harness layout of Aircraft A. Figure 26 shows the leg attachment system of aircraft B. Figure 27 and 28 show the lap belt anchorage and sash anchorage in Aircraft B. Figure 29 shows the lap belt and attachment points for aircraft C[95]. Some attachment points failed but it was concluded that these could be redesigned to withstand 25 G load levels with minimal penalty in cost or weight.

Chandler and Trout[96] tested the performance of an aftermarket shoulder harness that was attached to the seat belt of the (vacant) seat behind the occupant. They studied downward loading on the spine and looked for possible submarining. Impact tests were conducted in the 6 to 14 G range with resulting lap belt loads of 4.2 to 10 kN and shoulder belt loads of 3.1 to 9.1 kN. Figure 30[96] gives the spinal compressive load versus sled deceleration. Kevlar and long-elongation polyester webbing in 50 mm widths were tested statically and dynamically in a 4-point restraint system. They found 2 successive deceleration peaks in the dynamic testing as if caused by dummy rebound. No significant difference in performance was noted between the Kevlar and polyester webbing.

The Aviation Consumer[97] listed the retrofit shoulder harness kits available for Beech, Cessna and Piper G.A. aircraft. Some information was also provided about other aftermarket shoulder harnesses available.

The use of shoulder belt loads as injury criteria was discussed in Reference 12. It was concluded that these loads may not be appropriate because of changing belt geometry. Variables such as anchorage locations, seat height, seat stiffness and webbing characteristics are said to affect shoulder belt loads.

A selected group of 47 G.A. accidents was studied by Kirkham et al.[65]. Lap belt failures occurred in only 2 accidents. In one case the floor belt attachment broke. In a severe accident all lap belts failed. The results of estimates of the function of shoulder harnesses in the accidents are given in Table 12[65].

The U.S. Airforce studied the effects of restraint systems on acceleration loads in longitudinal and lateral directions. This information was made available in Reference 98. Table 13[76] lists the elongation and ultimate load properties of webbing used in U.S. Army helicopter restraint systems.

Rathgeber[99] subjected the seat and restraint system of the Cessna Caravan to dynamic tests according to the GASP[67] requirements. The occupant's forward motion was limited by

use of minimum elongation belt webbing. Restraint geometry was configured to minimize occupant submarining. Attachment points were also strengthened to react impact loads.

Jaerger et al.[100] discussed the various components of upper torso and the associated qualification tests of torso restraint systems intended for use in small fixed wing aircraft and rotorcraft. The SAE Aerospace Standard[101] was requested by the FAA to provide this technical information. The minimum static requirements call for: 1) 13.3 kN ultimate pelvic restraint load, 2) 11.1 kN ultimate upper torso restraint load, and 3) 11.1 kN webbing ultimate load with elongation of less than 20%. Testing of the other components is governed by the tests listed in Figure 31[100].

The FAA Advisory Circular[102] contains information necessary for shoulder harness installations (possibly on a retrofit basis) to withstand 20-25 G loads. It discusses

1) general features of shoulder harnesses,
2) restraint configurations, i.e. geometry of the restraint system with respect to the seat, occupant and aircraft cabin attachment points, and
3) attachment methods as related to position, aircraft construction and attachment hardware.

Figure 32[102] shows a possible arrangement for a single diagonal type harness.

The FAA static test procedures for body blocks for the testing of restraint systems are described in Reference 103. It is necessary to measure the loads carried by the restraint anchor points and by the seat legs when static loads are applied to the body blocks. The body blocks are restrained by seat belts and shoulder harnesses in typical installations.

7.0 General Aviation Aircraft Floor Structures

Crashworthy aircraft structure should include: 1) a high strength cage for occupant volume protection, 2) restraint of potential free-flying objects, and 3) strong floors. Seats should remain fixed in a crash and floor deformation should not interfere with the stroking of energy absorbing seats.

Energy absorbing concepts can be incorporated in G.A. aircraft subfloor structures. The floor and subfloors must be dual purpose, i.e. they must support airframe and seat loads in normal flight and then also crush to absorb energy in a crash. In this way, only a small weight penalty is incurred.

Floor distortions are discussed in Reference 58 and generally they occur as bulges or dishes as well as overall warpages. Distortions influence seat strength and stiffness. The

torsional rigidity of the seat pan governs the forces transmitted from the floor. The recommended limits of floor distortion in the design of seats are shown in Figure 33 and 34[58]. Floor distortions are also discussed in Reference 104.

Carden and Hayduk[105] studied the response of G.A. aircraft subfloors to crash pulses. Figure 35 [105] illustrates the concept of available stroke to dissipate energy in a crash. Choosing a human upward tolerance of 25 G, a velocity change of 12.2 m/sec. can be accommodated in a stroke distance of 0.3 m. A floor crush of 0.15 m will dissipate the crash pulse associated with an 8.2 m/sec. velocity change.

Cronkhite[106] and Cronkhite and Berry[107] reported on the full-scale testing of G.A. aircraft fuselage sections to develop crashworthy floor sections. The fuselage design philosophy is shown in Figure 36. In a G.A. aircraft the high strength rigid floor of 50 mm typical thickness supports the seats. The lower section of about 150 mm is comprised of crushable structure. The lower part of Figure 36 shows the difference in energy absorbed (area beneath the load-deflection curve) between a conventional fuselage and a crushable one. Figure 37 shows five energy absorbing elements for incorporation into crushable floors. Figure 38 shows the load deflection curves for four of the more promising energy absorbing concepts. The weight penalty of these structural additions is only about 1/4% of the total weight of the aircraft.

Carden[108] conducted tests on two G.A. floor structures at NASA Langley. The aircraft were of 3400 kg weight, six occupant capacity, one of which was tested unmodified. Two aircraft were tested with modified floors as depicted in Figure 39. Figures 40 and 41 show the floors in greater detail. Figure 42 shows the reduction in normal (vertical) floor accelerations at three locations.

8.0 Recommendations for Further Research and Development in G.A. Crashworthiness: Seats, Restraints and Floor Structures

Recent Canadian accident statistics[109] do not show any significant deviations from the trends evident in the U.S. G.A. accident picture. The Canadian Aviation Safety Board (CASB) study[109] indicated a slight reduction in small plane accident rates beginning in 1982. This trend has been attributed to economic factors and the efforts of safety programs. The percentage of accidents resulting in fatalities has, however, remained unchanged showing that survivability has not improved.

Canadian research and development activity in G.A. crashworthiness is limited . Some seat manufacturers are preparing to meet the new dynamic requirements of FAA FAR 23 and

require test facilities and the development of mathematical techniques to complement or replace seat tests.

Small scale R & D efforts in G.A. will do little to ameliorate accident effects due to the complexities inherent in the areas of safety. Accident statistics, past and present, corroborate the need for a comprehensive, multi-discipline effort by several Canadian institutions.

A general research program in G.A. crashworthiness should be based on a systems approach and include the further study of biodynamic response, impact testing of full-scale aircraft and/or seats, restraints and anthropomorphic dummies as well as analytical modelling of all crash events.

Specific research tasks concerning seats, restraints and floor structures have been identified as:

1) development of energy absorbing materials such as cushions for seat retrofit or for original installation of seats,
2) mathematical modelling of the interactions of an occupant, seat and restraints during a crash sequence that can be used to design retrofit and new installations,
3) dynamic mathematical modelling of floor and subfloor structures,
4) development of methods of analysis to complement dynamic testing of seats.

Rothe et al [59], Vulcan et al [60], and Hearon and Brinkley [80] studied energy absorbing elements such as cushions for retrofit or for use as original equipment for seats. Sufficient stroking in an energy absorber is necessary to provide protection in crashes having a significant vertical velocity component. Research efforts should continue in the development of energy absorbing elements and materials.

Several seat/occupant models exist [46, 53] to study the complex interaction of occupant, seat and restraints. Some of these models can be integrated with the dynamic structural analysis of floors and subfloors. These analyses are required to define the requirements for retrofit and new designs.

The introduction of the FAA regulations [68] on dynamic testing of G.A. aircraft seats increases the need for mathematical analysis in conjunction with the expansion of impact test facilities. The use of mathematical models will be required to assist the planning and analysis of seat tests according to the new regulations.

9.0 Conclusion

An effective way to increase occupant protection in G.A. aircraft in survivable crashes is the promotion of education for the usage and maintenance of currently installed seat and shoulder harnesses. Several studies have shown that the percentage of usage of installed shoulder harness is only about 40%. The installation of shoulder harnesses (about 60% of G.A. aircraft seats do not have shoulder harnesses) would provide an immediate benefit. Retrofit work entails engineering design of attachment points for the many different models of G.A. aircraft in use. Retrofit kits are available for some G.A. aircraft.

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TABLE 1 RATIO OF FATAL ACCIDENTS TO TOTAL ACCIDENTS [REF. 5] 1964 - 1967

LOW

Cessna 120/140	0.058	Piper PA-32**	0.104
Cessna 180	0.061	Mooney	0.104
Luscombe	0.063	Cessna 172	0.106
Piper PA-12	0.064	Aeronca	0.109
Ercoupe	0.068	Piper PA-24	0.116
Cessna 150	0.069	Beech 35	0.121
Beech 23*	0.070	Piper PA-23	0.125
Cessna 205/210	0.077	Navion	0.127
Globe Swift	0.078	Cessna 175	0.131
Piper PA-22	0.080	Beech Twins	0.150
Piper PA-28	0.084	Piper J-3/PA-11	0.151
Cessna 170	0.085	Taylorcraft	0.156
Cessna 310	0.088	Piper PA-18	0.168
Cessna 182	0.095	Aero Commander	0.199
Stinson	0.102	Piper PA-30	0.201

HIGH

* 1966-1967 only
** 1967 only

TABLE 2 MATRIX OF AIRPLANE CONFIGURATIONS AND MAXIMUM TAKEOFF WEIGHT AND USAGE [REF. 10]

MAXIMUM TAKEOFF WEIGHT (lb)	SINGLE-ENGINE LOW-WING	SINGLE-ENGINE HIGH-WING	TWIN-ENGINE LOW-WING	TWIN-ENGINE HIGH-WING
< 2000	Trainer Utility	Aerobatic Pleasure Trainer		
2000 - 2499	Trainer Sport Utility Pleasure	Trainer Business Aerobatic Utility Pleasure		
2500 - 3999	Business Agriculture Commuter Trainer Utility Pleasure	Business Utility Cargo-Freight Commuter Pleasure		
4000 - 5999	Agricultural (a)		Business Commuter Cargo	Business Commuter
6000 - 7999			Business Commuter Cargo/Freight	Business Commuter Cargo/Freight
8000 - 12500				Business Commuter

(a) Consists of one low-wing and one biplane

TABLE 3 RELATIONSHIP OF GENERAL AVIATION AIRPLANE CONFIGURATIONS TO PERFORMANCE PARAMETERS, USAGE AND OCCUPANT CAPACITY [REF. 10]

AIRPLANE CONFIGURATION	MAXIMUM TAKEOFF WEIGHT (lb)	STALL SPEED RANGE FLAP DOWN (knots)	CRUISE SPEED RANGE 75 PERCENT MAX. POWER (knots)	PRIMARY USAGE	OCCUPANT CAPACITY
Single-Engine Low-Wing	< 2500	49 - 54	108 - 128	Training Pleasure	1 - 4
Single-Engine High-Wing	< 2500	38 - 45	100 - 114	Training Pleasure Aerobatics	2 - 4
Single-Engine Low-Wing	2500 - 4000	49 - 61	132 - 176	Business Commuting Training Utility	4 - 7
Single-Engine High-Wing	2500 - 4000	45 - 59	124 - 163	Business Utility Cargo	4 - 7
Single-Engine (a) Low-Wing	2900 - 6000	47 - 59	101 - 138	Agriculture	1
Twin-Engine Low-Wing	3700 - 10900	59 - 82	162 - 247	Commuting Business Cargo Commuting	4 - 17 (b)
Twin-Engine High-Wing	4600 - 10250	61 - 77	170 - 280	Business Cargo Commuting	4 - 11

(a) includes one biplane

(b) 17 occupants for 1 airplane only, otherwise maximum is 11

TABLE 4 STRUCTURAL DESIGN CHARACTERISTICS OF CURRENT GENERAL AVIATION AIRPLANES [REF. 10]

STRUCTURE	CATEGORY 1 SINGLE-ENGINE LOW OR HIGH WING WEIGHT < 2500 lb	CATEGORY 2 SINGLE-ENGINE LOW OR HIGH WING WEIGHT 2500 - 4000 lb	CATEGORY 3 SINGLE-ENGINE LOW-WING (a) AGRICULTURAL USE ONLY WEIGHT 2500 - 4000 lb	CATEGORY 4 TWIN-ENGINE LOW OR HIGH WING WEIGHT 4000 - 10900 lb
Wing	o Braced wing 1,2 or 3 spar, mostly metal, some wood spars o Cantilever 1,2 or 3 spar, mostly metal, some wood spars	o Cantilever 1,2 or 3 spar, mostly metal, some wood spars	o Braced 1 or 2 spar, metal construction	o Cantilever 1,2 or 3 spar, mostly metal, some wood spars o One braced, all metal
Fuselage	o All metal semi-monocoque o Rectangular section welded steel tube o Keel formed by floor and lower skin (cabin), semi-monocoque (rear)	o All metal semi-monocoque o Weld steel tube o Welded steel tube (cabin), semi-monocoque (rear)	o Rectangular section welded steel tube o Welded steel tube (cabin), semi-monocoque (rear) o Long nose section o Isolated occupant region o Strong turnover structure	o All metal semi-monocoque
Engine Attachment	o Tubular	o Tubular o Keel	o Tubular	o Tubular o Keel
Landing Gear	o Tail wheel o Tricycle o Cantilever spring main gears o Nonretractable	o Tail wheel retractable o Tricycle retractable and nonretractable o Cantilever spring main gear o Hydraulically activated system	o Tail wheel type o Nonretractable o Cantilever spring main gears	o Mostly tricycle retractable o Some non-retractable with cantilever spring main gears o Hydraulic or electro-mechanical actuated system
Tail Unit	o Cantilever all metal o Welded steel tube and channel with fabric covering	o Cantilever all metal	o Welded steel tube o Cantilever all metal	o Cantilever all metal

(a) with the exception of one biplane

TABLE 5 MAIN FEATURES OF MATHEMATICAL MODELS [REF. 46]

	DISCRETE EL. MODELS	FINITE EL. MODELS
NO. OF DOF	100 - 1000	1000 - 20000
Integration Scheme	Explicit: KRASH, VEDYAC, HSM Implicit: ATB, MADYMO	Explicit: DYCAST Implicit: DYCAST, CRASHMAS, HEMP/ESI, DYSMAS/L
Contact Simulation	Macrosurface interf.: VEDYAC, ATB, MADYMO, HSM Non-linear spring: KRASH	FE Contact Processor: CRASHMAS, DYSMAS/L, HEMP/ESI Non-linear spring: DYCAST
Failure Modes	Disappearance of structural connections: VEDYAC	Erosion mode: DYSMAS/L, HEMP/ESI Crack opening mode: CRASHMAS, DYSMAS/L
Experiments Required	Macroelements properties Validation	Material properties Validation
Main Purposes	Parametric investigations Biomechanical models	Detail analyses of structures and subcomponents

TABLE 6 INCIDENCE OF SEAT FAILURES [REF. 65]

SEATING POSITION	ATTACHMENTS			LEGS/PEDESTALS			BACK		
	FAILURES	TOTAL #	%	FAILURES	TOTAL #	%	FAILURES	TOTAL #	%
Pilot	19	44	43	10	46	21	2	44	5
Copilot	16	39	41	9	38	24	4	39	10
1A	4	16	25	2	16	13	0	15	
1B	6	17	35	2	17	12	0	16	
2A	2	6	33	1	6	17	1	6	17
2B	1	6	17	1	6	17	1	6	17
3A	0	1		0	1		0	1	
3B	0	1		0	1		0'	1	

TABLE 7 CONTRIBUTION OF SEATS TO SEVERITY OF INJURY [REF. 65]

SEAT POSITION	SEAT CONTRIBUTED TO SEVERITY	SEAT DID NOT CONTRIBUTE TO INJURY	UNDETERMINED
Pilot	16	26	5
Copilot	11	26	3
Passengers	14	34	1
Total	41	86	9
Percent	30	63	7

TABLE 8 JAARS DYNAMIC SEAT TESTS [REF. 66]

	Vertical Input Acceleration		Floor N		Floor L		Seat Pan N		Seat Pan L		Pelvis N		Pelvis L	
JAARS Seat Test	G_{max}	ΔT (sec)	G_{max}	ΔT (sec)	G_{max}	ΔT (sec)	G_{max}	ΔT (sec)	G_{max}	ΔT (sec)	G_{max}	ΔT (sec)	G_{max}	ΔT (sec)
1	-21.6	.093	-15.9	.088	-13.2	.092	-17.1	.083	-17.0	.091	-27.8	.070	-14.9	.093
2	-22.1	.087	-20.1	.088	-9.9	.092	-22.5	.091	-7.1	.096	-31.4	.077	-13.5	.054
3	-20.7	.084	-21.5	.080	+1.5	.049	---	---	---	---	-25.7	.083	+18.3	.074
4	-18.6	.086	-16.4	.083	-9.6	.089	---	---	---	---	-29.0	.069	-4.5	.035
5	-18.2	.088	-16.8	.085	-8.6	.089	-17.1	.084	-10.4	.087	-27.8	.068	-10.1	.063

TABLE 9 1964 - 1973 SHOULDER HARNESS INSTALLATION [REF. 89]

	NEW GENERATION	OLD GENERATION
Accidents	1790	1471
Installed	976 (54.5%)	904 (61.5%)
Not installed	10 (0.6%)	34 (2.2%)
Unknown/not reported	628 (35%)	364 (24.8%)
Other	6 (0.34%)	10 (0.68%)
No record	170 (9.5%)	160 (10.9%)

TABLE 10 1964 - 1973 INJURY EXPERIENCE VERSUS SHOULDER HARNESS USE [REF. 89]

	NEW GENERATION			OLD GENERATION		
SHOULDER HARNESS USE	PERSONS INVOLVED	FATAL	SERIOUS	PERSONS INVOLVED	FATAL	SERIOUS
Installed-used-held	910	85 [9.3%]	112 [12.3%]	829	131 [15.8%]	109 [13.2%]
Installed-used-failed	52	18 [34.7%]	21 [40.3%]	30	14 [46.6%]	7 [28.4%]
Installed-not used/not installed	26	10 [38.4%]	4 [15.4%]	83	28 [33.7%]	15 [18.1%]
Unknown/ not reported	628	30 [4.8%]	48 [7.6%]	364	43 [11.8%]	19 [5.2%]

TABLE 11 HUMAN SUBJECT TESTS, RESTRAINED BY 3" WIDE LAP BELT [REF. 92]

FORCE, lb.	PEAK G	ONSET RATE G/sec	TIME DURATION sec	RESPONSE
FORWARD-FACING ($-G_x$):				
4290	15	300	0.002	Subjective pain threshold limit with no significant injury highest voluntary level tested; transient injury, minor reversible injury.
	11.4-32.0	280-1600	0.002	
	26	850	0.002	
	~ 30	~ 1500		
REARWARD-FACING ($+G_x$):				
	30	1065	0.110	No injury.
	40	2000		Severe but transient response.
	82.6 (chest) 40.4 (sled)	3800	0.040	Highest voluntary measured test, transient injury.
	> 45		0.100	Estimated injury threshold Air Force design limit.
LATERAL ($\pm G_y$):				
	9 (average)		0.100	Subjective pain threshold.
	14.1	600	0.122	Maximum voluntary pain level.

TABLE 12 ESTIMATES OF VALUE OF UPPER TORSO RESTRAINTS TO OCCUPANTS [REF. 65]

	OCCUPIABLE AREA DAMAGE INDEX						
NUMBER OF:	MINIMUM	MODERATE	SEVERE	MODERATELY SEVERE	EXTREMELY SEVERE	EXTREME	TOTAL
Accidents	8	15	12	7	1	4	47
Persons	23	41	31	22	4	15	136
Pilots would have been helped	7	13	12	6	1	4	43
Pilots would not have been helped	1		1	1		1	4
Copilots would have been helped	6	10	10	6	1	3	36
Copilots would not have been helped	1		1	1		1	4
Passengers would have been helped	8	16	8	5		5	42
Passengers would not have been helped		1		4		2	7

TABLE 13 RESTRAINT SYSTEM WEBBING [REF. 76]

COMPONENT	THICKNESS (in.)	WIDTH (in.)	AVERAGE ELONGATION AT DESIGN LOAD (%)	ULTIMATE LOAD (lb.)	DESIGN LOAD (lb.)
Lap Belt	0.057	2.25	7.5	8880	4000
Tiedown	0.057	1.78	7.5	6980	3000
Shoulder Straps	0.057	2.03	7	7800	4000

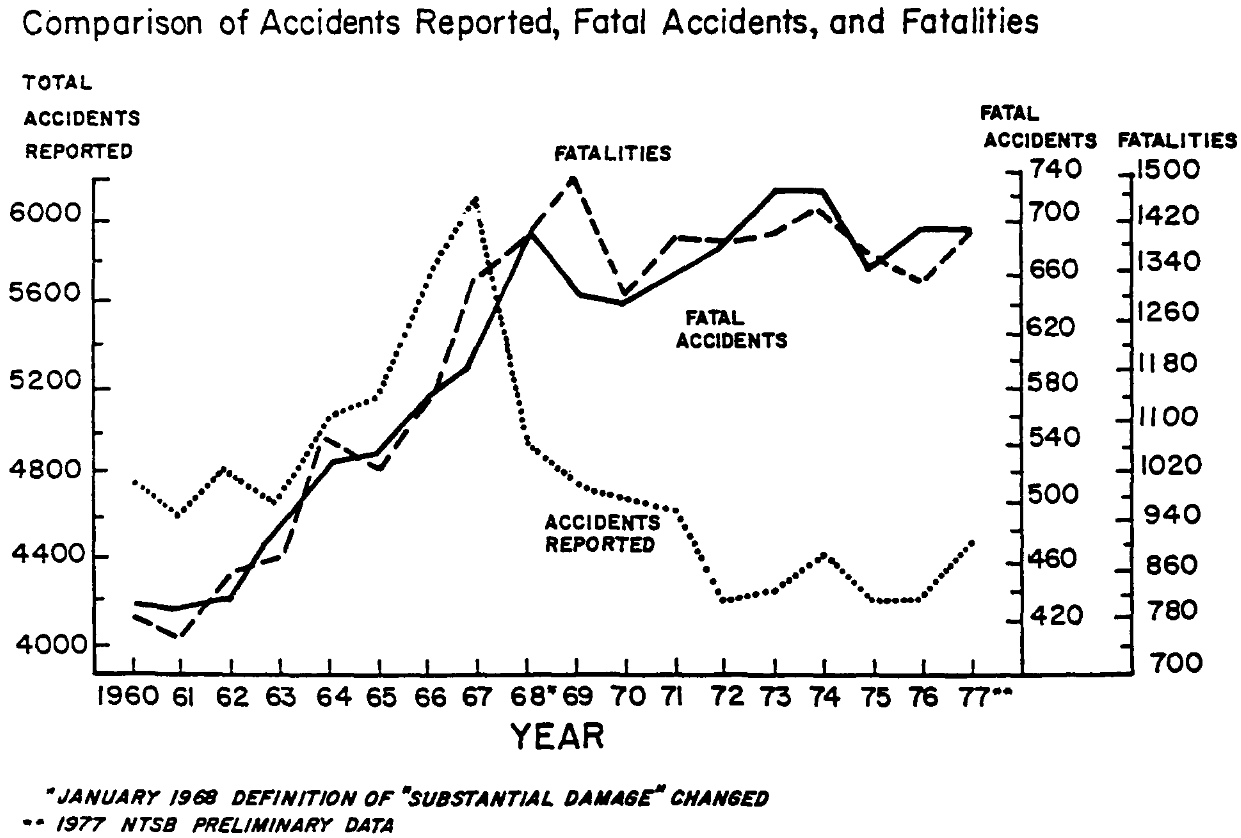


FIG. 1: GENERAL AVIATION ACCIDENTS 1960 - 1977 [REF. 8]

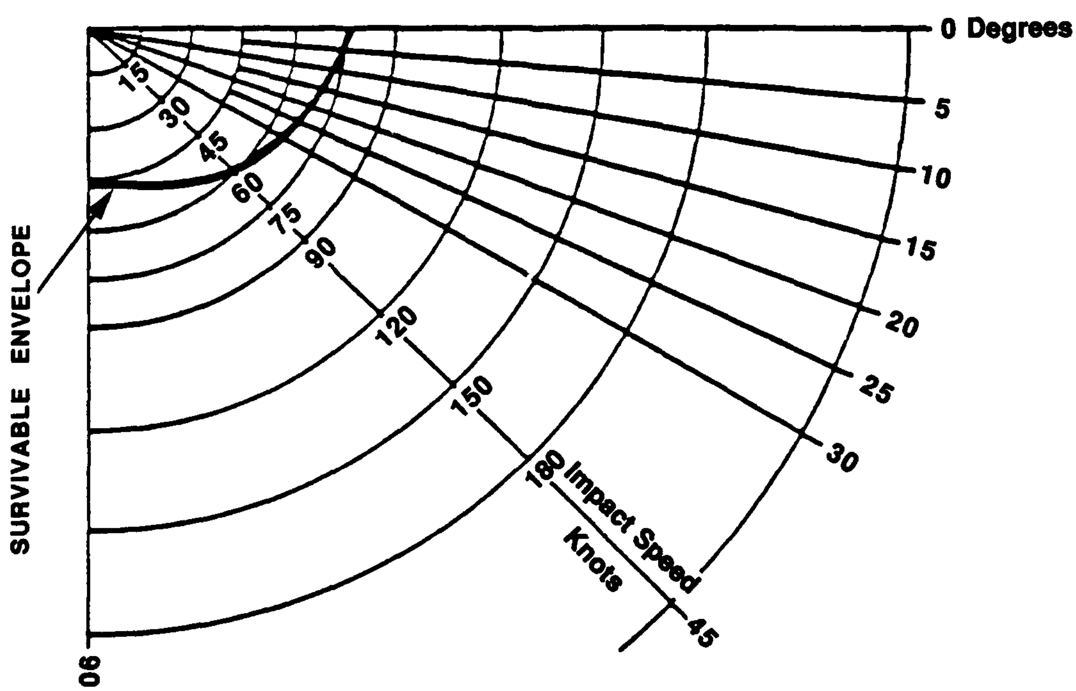


FIG. 2: SURVIVABLE ENVELOPE FOR GENERAL AVIATION ACCIDENTS [REF. 9]

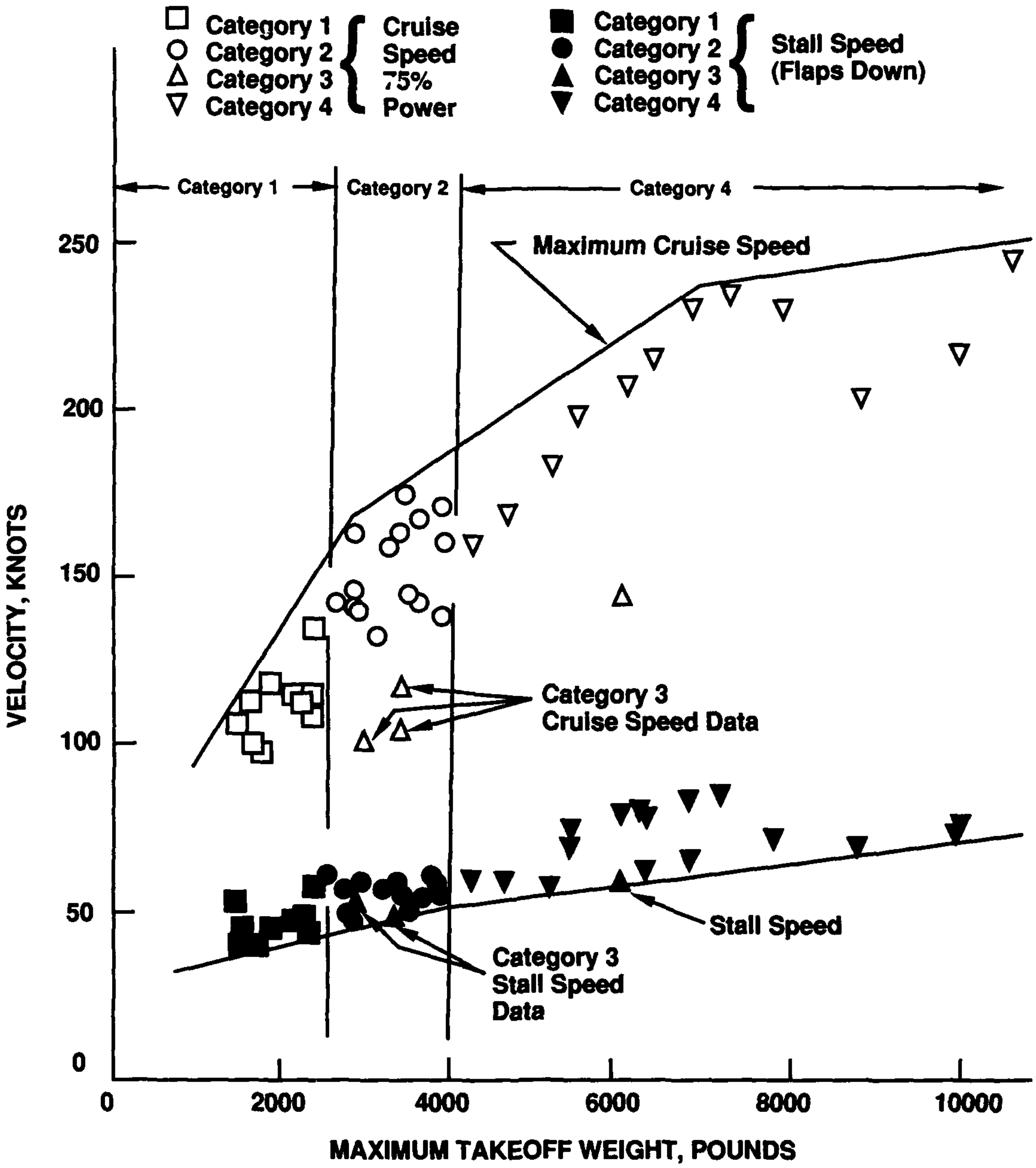


FIG. 3: OPERATIONAL VELOCITY/WEIGHT ENVELOPE FOR CURRENT GENERAL AVIATION AIRPLANES [REF. 10]

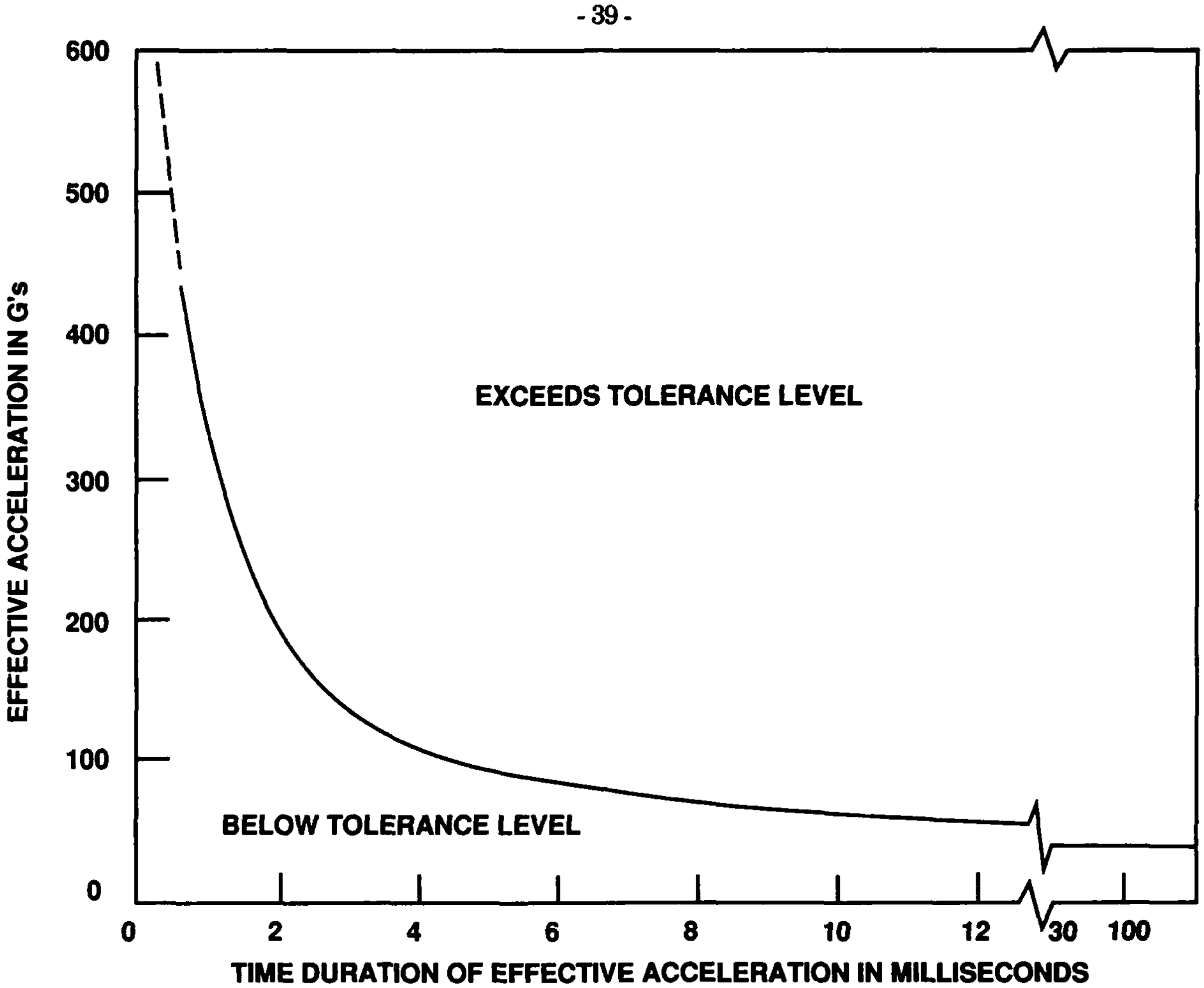


FIG. 4: IMPACT TOLERANCE FOR THE HUMAN BRAIN IN FOREHEAD IMPACTS AGAINST PLANE, UNYIELDING SURFACES [REF. 12]

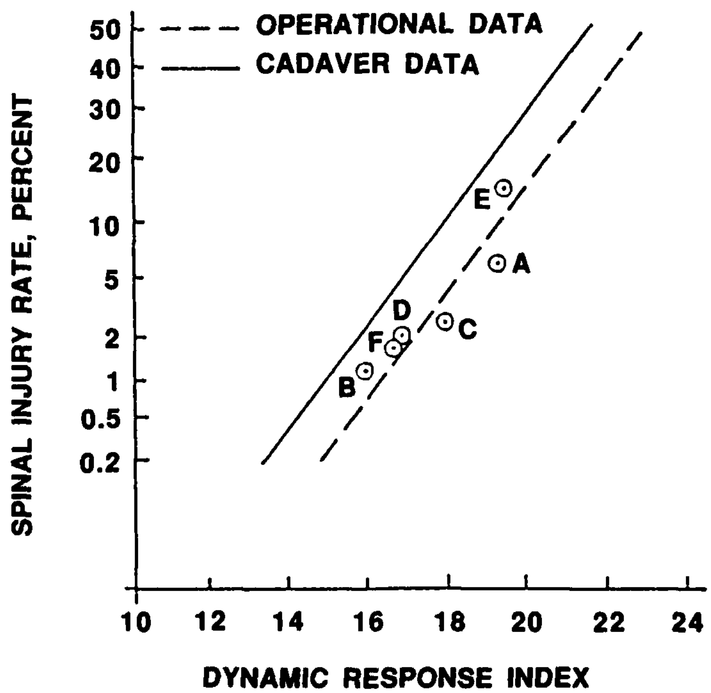


FIG. 5: CORRELATION BETWEEN DYNAMIC RESPONSE INDEX AND SPINAL INJURY RATE FOR EJECTION SEATS [REF. 26]

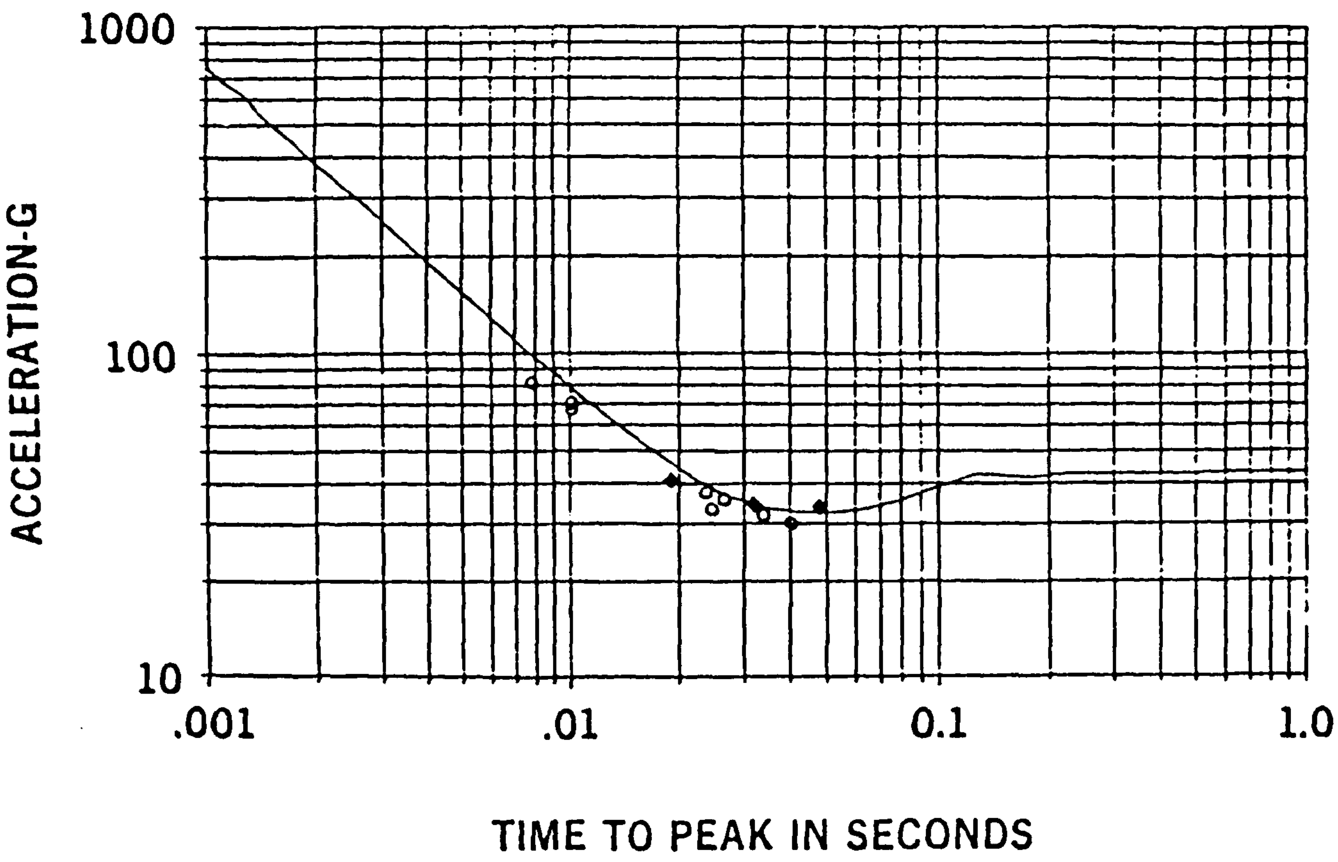


FIG. 6: MODEL RESPONSE CURVE FOR +X AXIS HALF-SINE ACCELERATION PULSES [REF. 32]

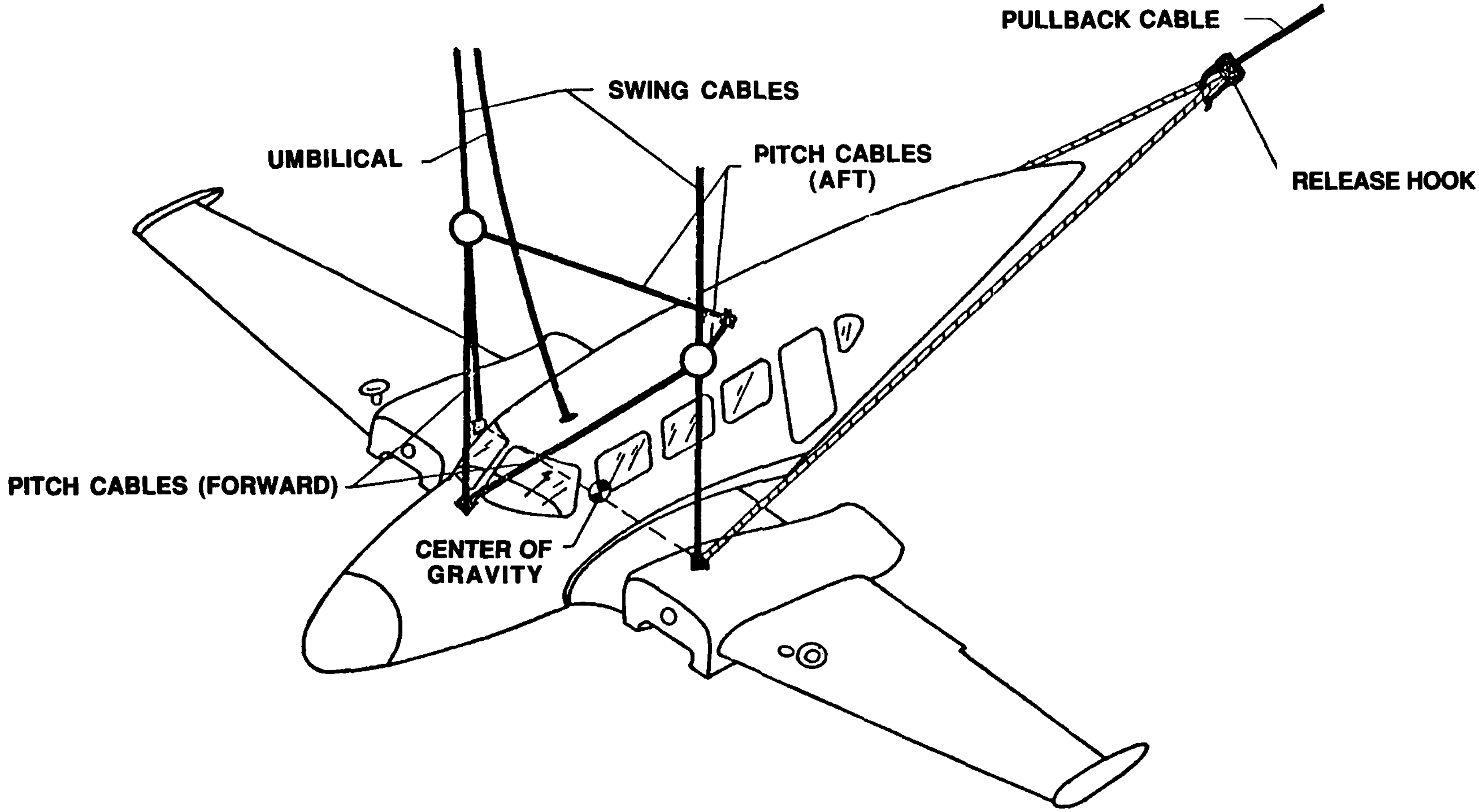


FIG. 7: SUSPENSION SYSTEM [REF. 37]

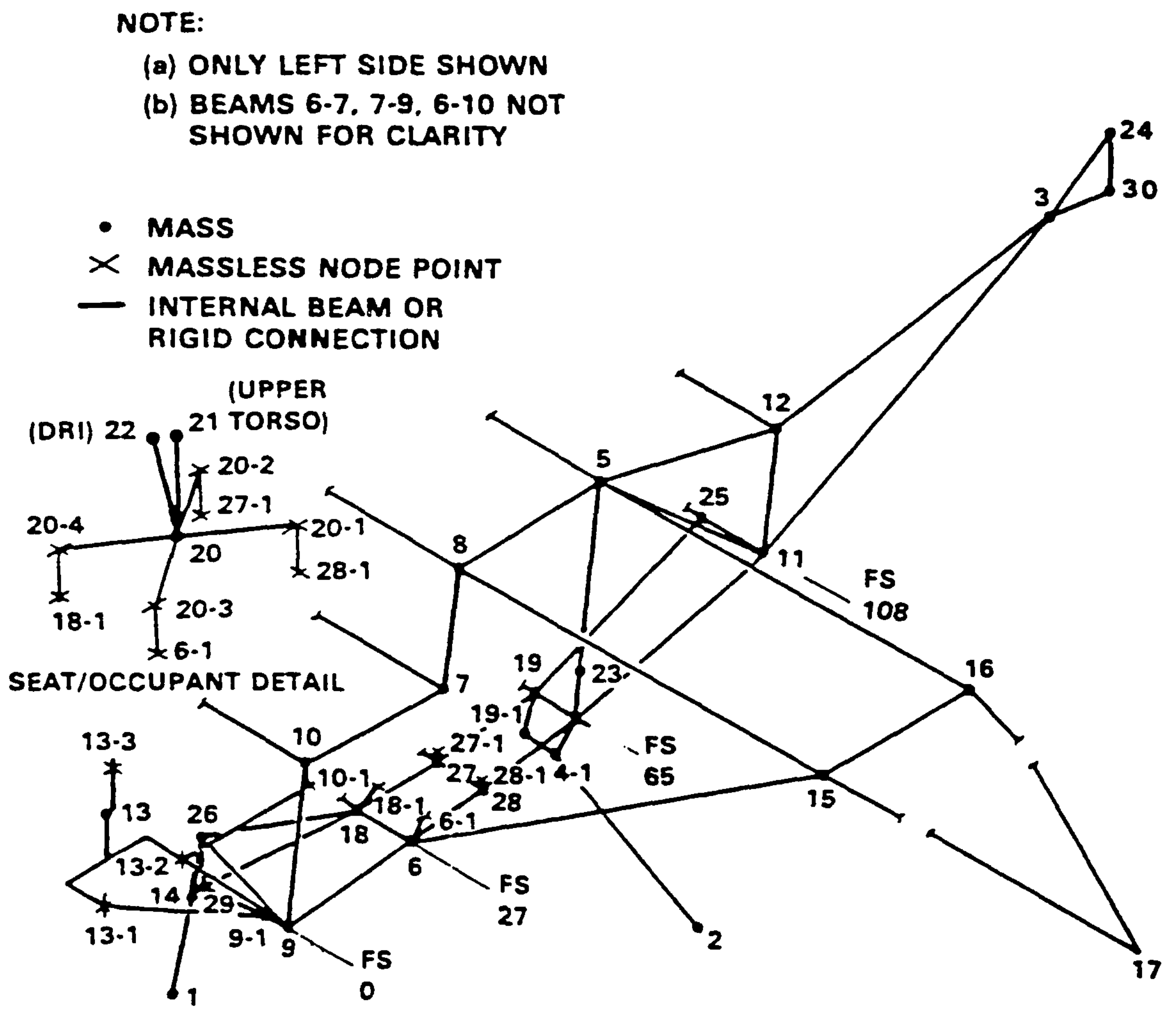


FIG. 8: GENERAL AVIATION AIRPLANE *KRASH* MODEL [REF. 43]

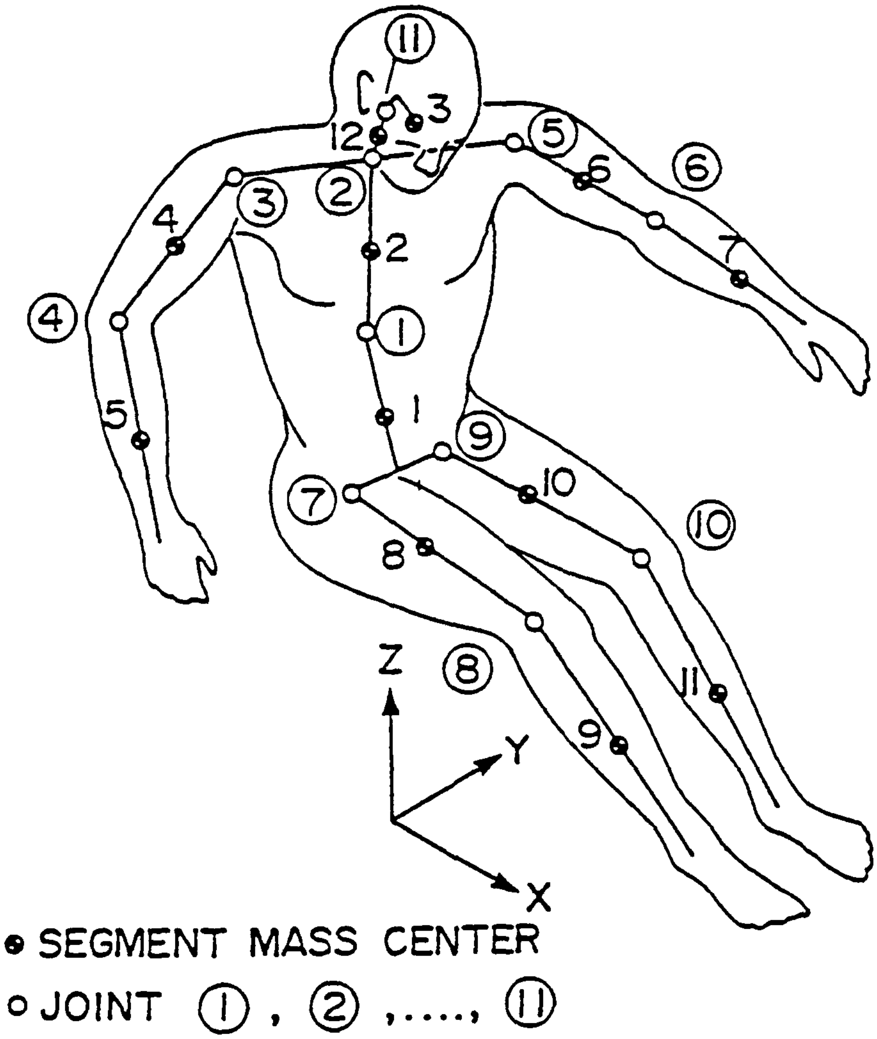


FIG. 9: GENERAL THREE-DIMENSIONAL OCCUPANT MODEL [REF. 52]

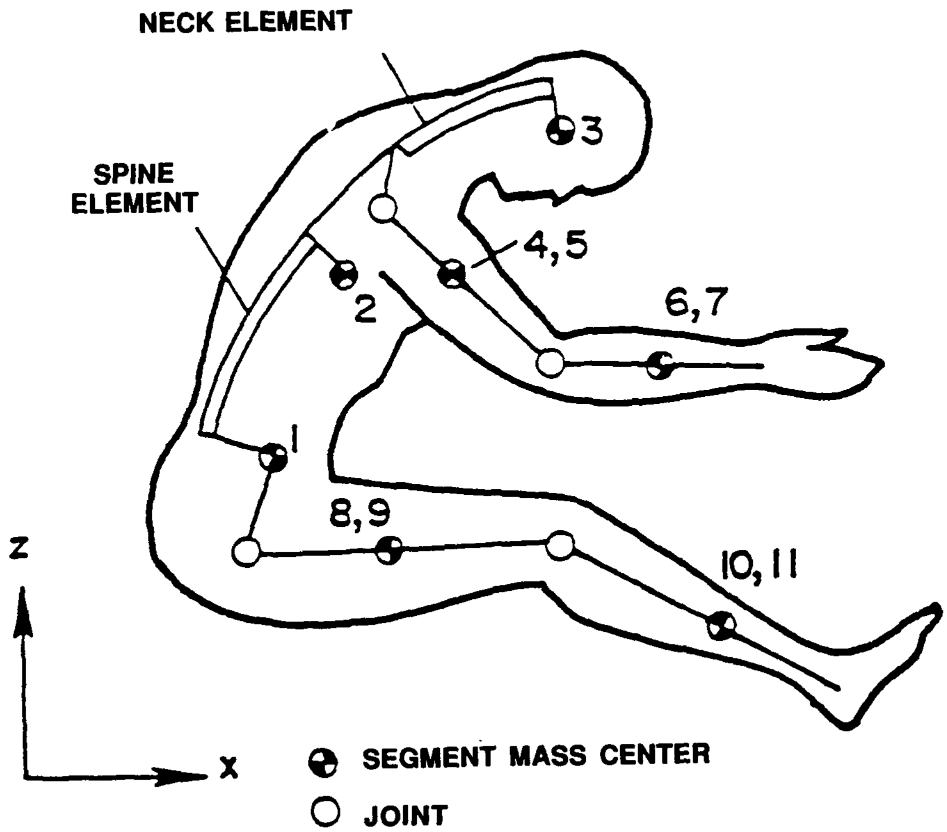


FIG. 10: PLANE-MOTION OCCUPANT MODEL [REF. 52]

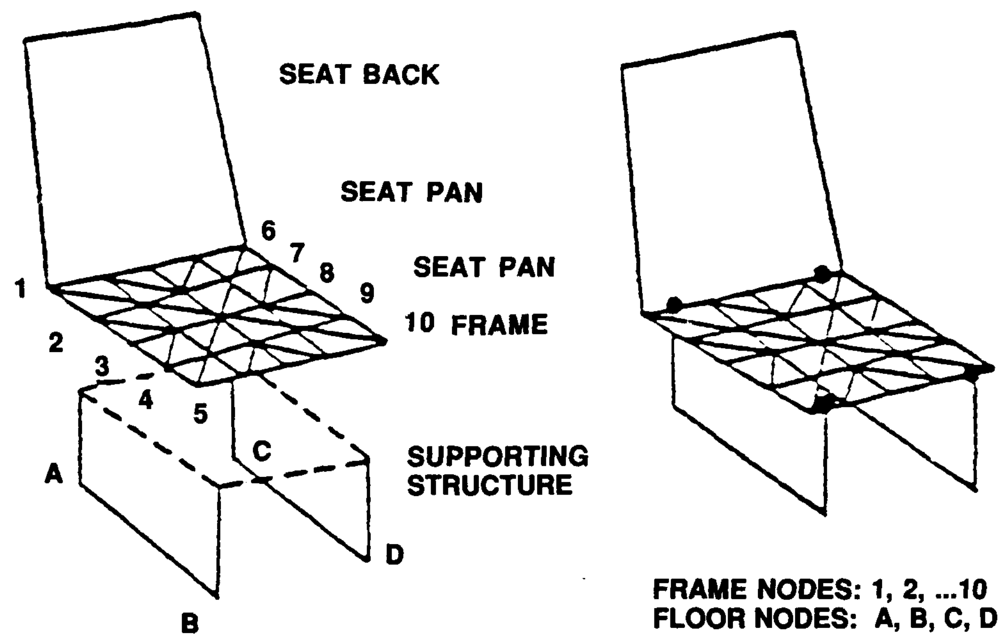


FIG. 11: SEAT MODEL COMPONENTS [REF. 51]

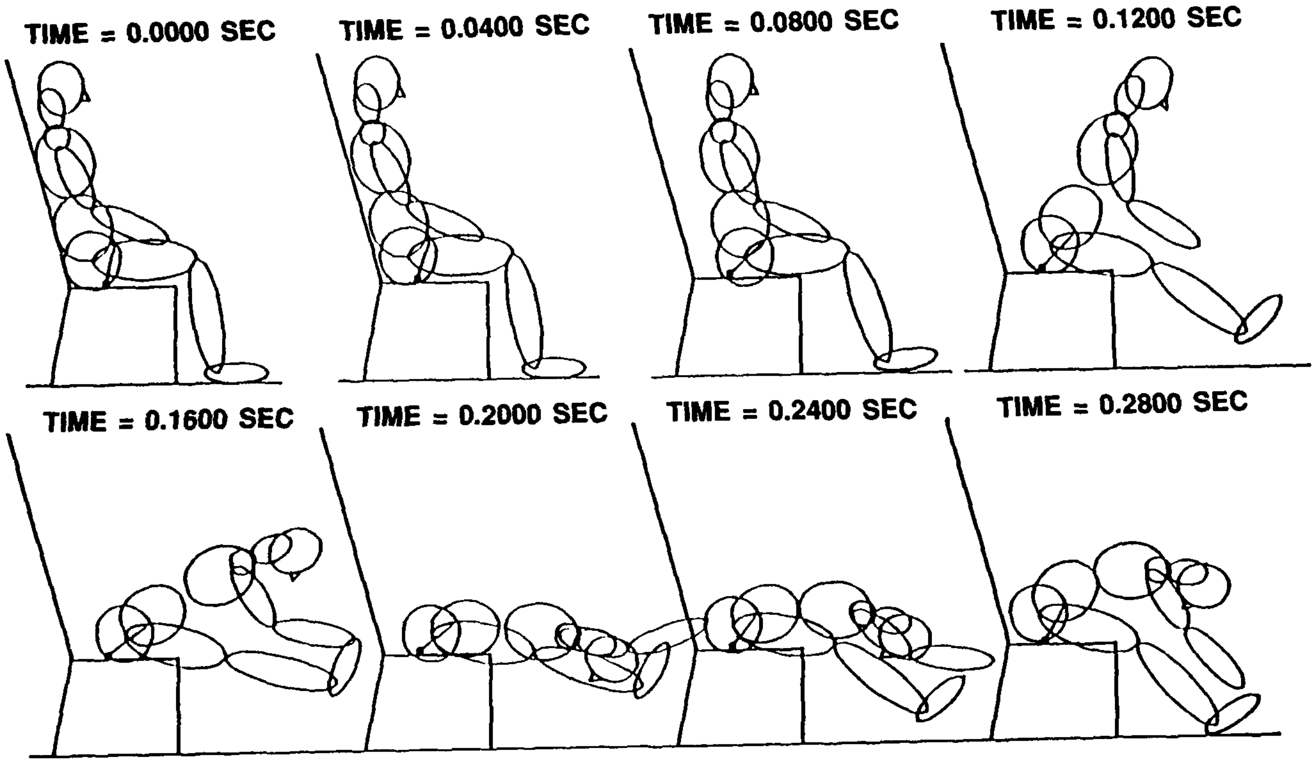


FIG. 12: OCCUPANT RESPONSE TO IMPACT OF CHEST AND HEAD ON LEGS IN LAP BELT-ONLY SIMULATION [REF. 52]

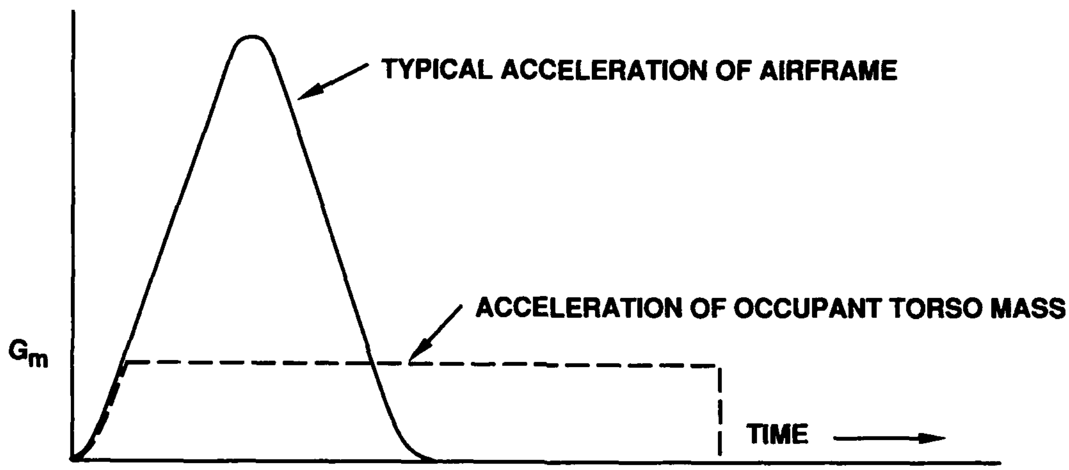
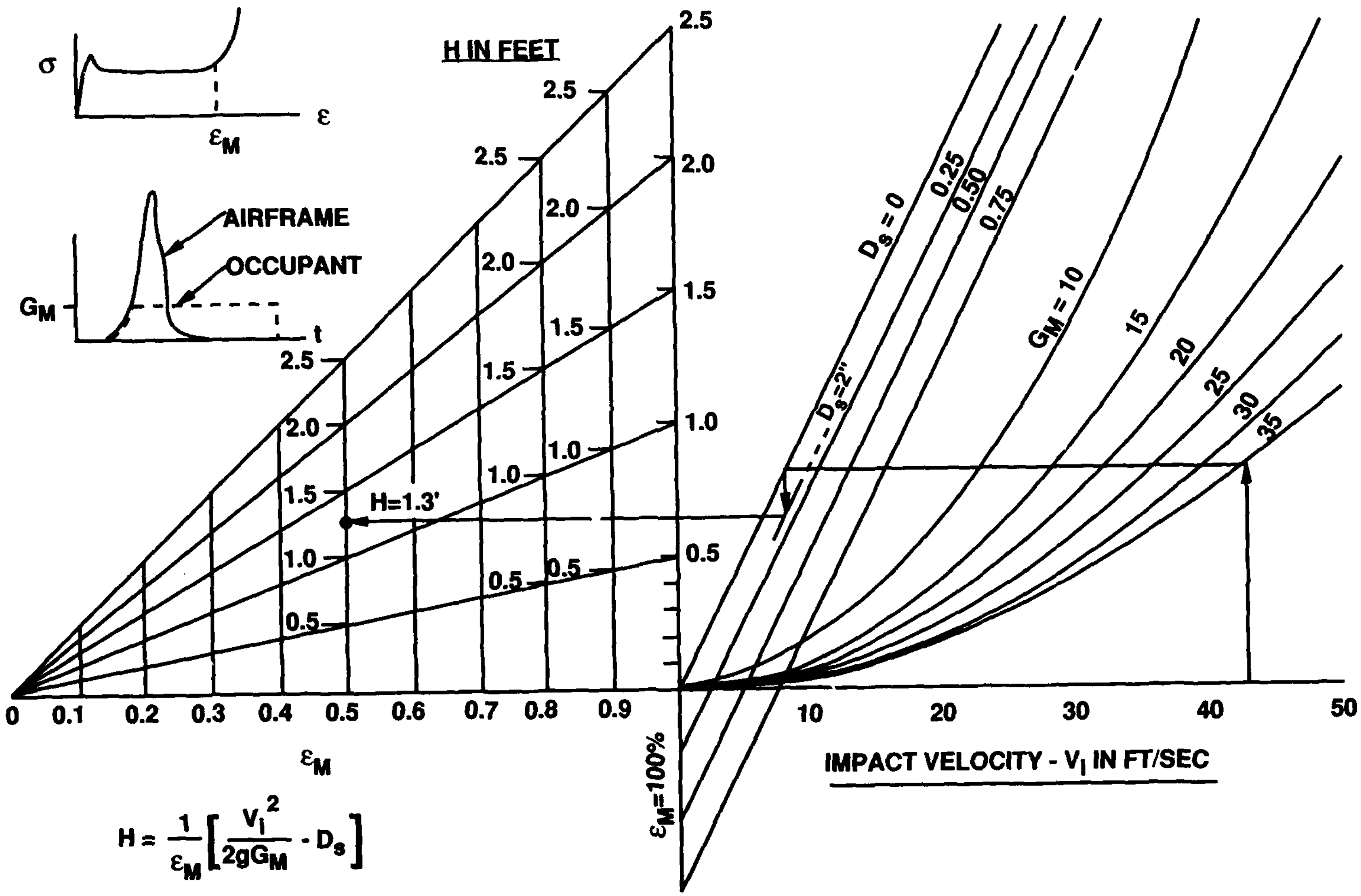


FIG. 13: ASSUMED ACCELERATION OF FLOOR AND OCCUPANT [REF. 59]



$$H = \frac{1}{\varepsilon_M}\left[\frac{V_I^2}{2gG_M} - D_s\right]$$

FIG. 14: CUSHION THICKNESS H AS A FUNCTION OF G_M, V_I, ε_M, D_s [REF. 59]

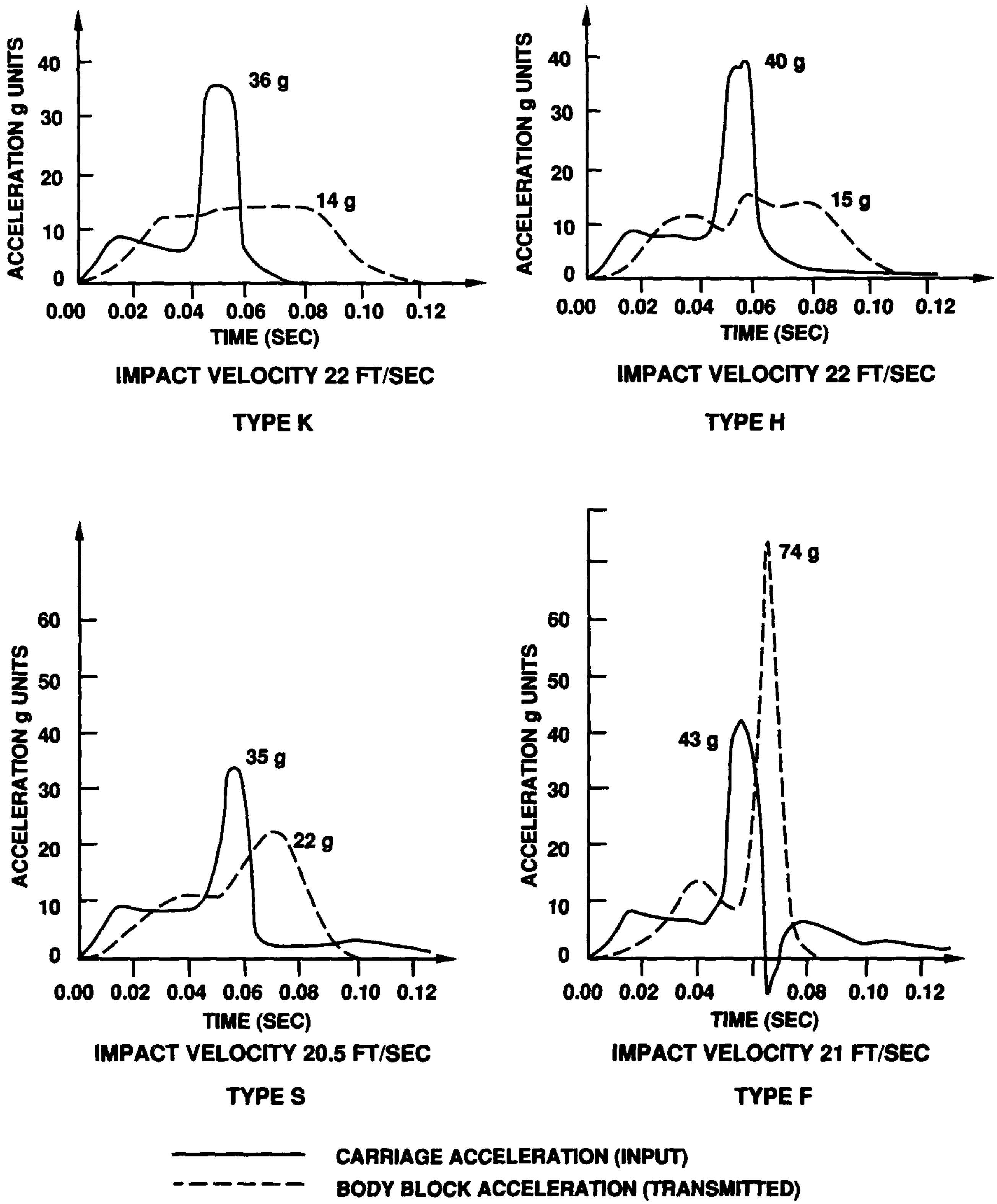


FIG. 15: CARRIAGE AND BODY BLOCK ACCELERATIONS [REF. 60]

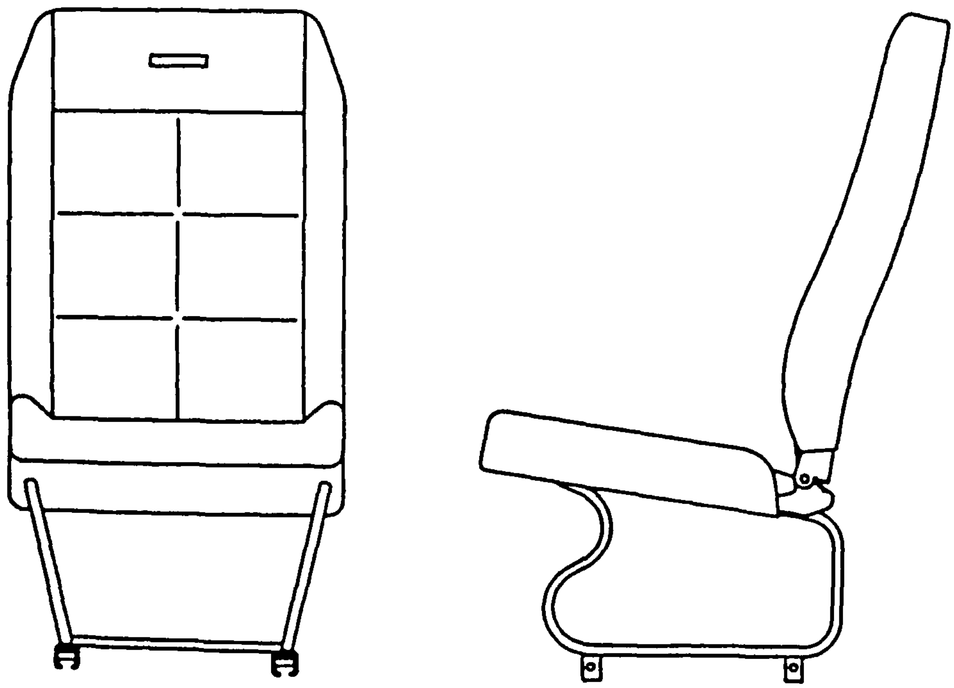
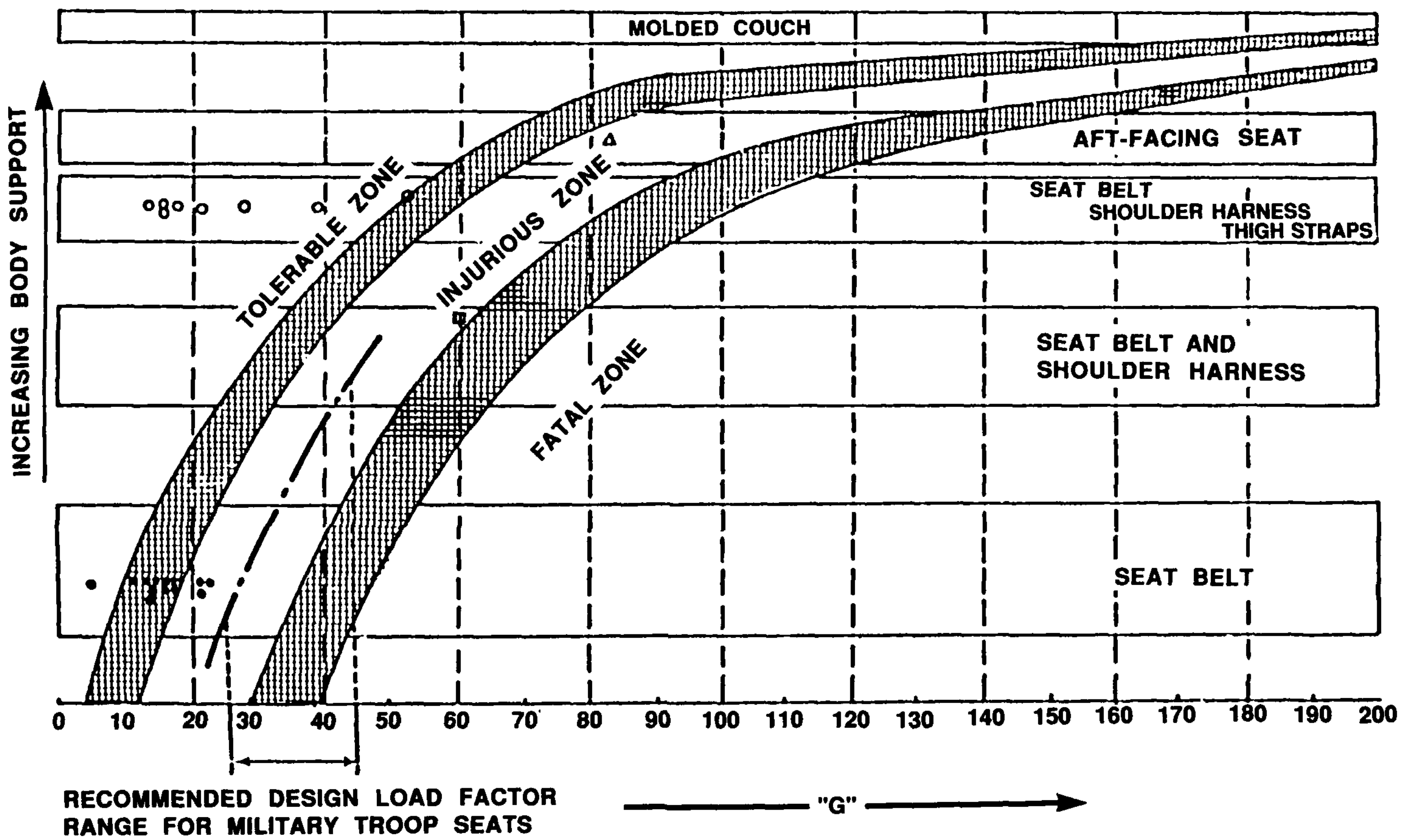


FIG. 16: SECOND SEAT DESIGN [REF. 61]



(THE SHADED AREAS INDICATE TRANSITION BETWEEN THE TOLERABLE, INJURIOUS AND FATAL DECELERATION LIMITS.)

FIG. 17: HYPOTHETICAL CORRELATION OF RESTRAINT SYSTEMS AND HUMAN TOLERANCE TO ABRUPT TRANSVERSE DECELERATION FOR DURATIONS FROM .001 TO 0.10 SECOND [REF. 59]

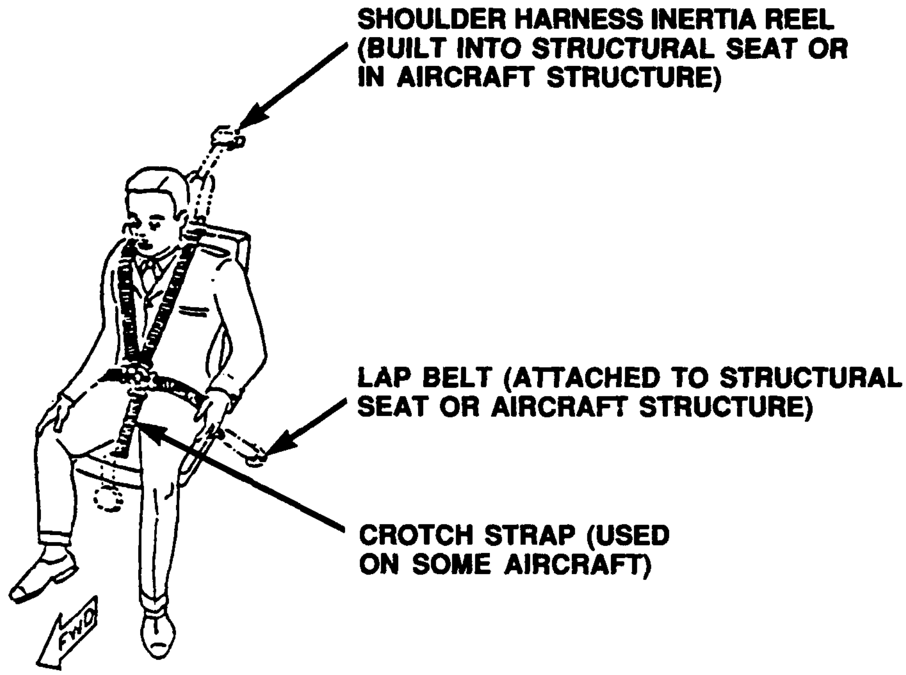


FIG. 18: GENERAL AVIATION — DUAL SHOULDER STRAP RESTRAINT SYSTEM [REF. 88]

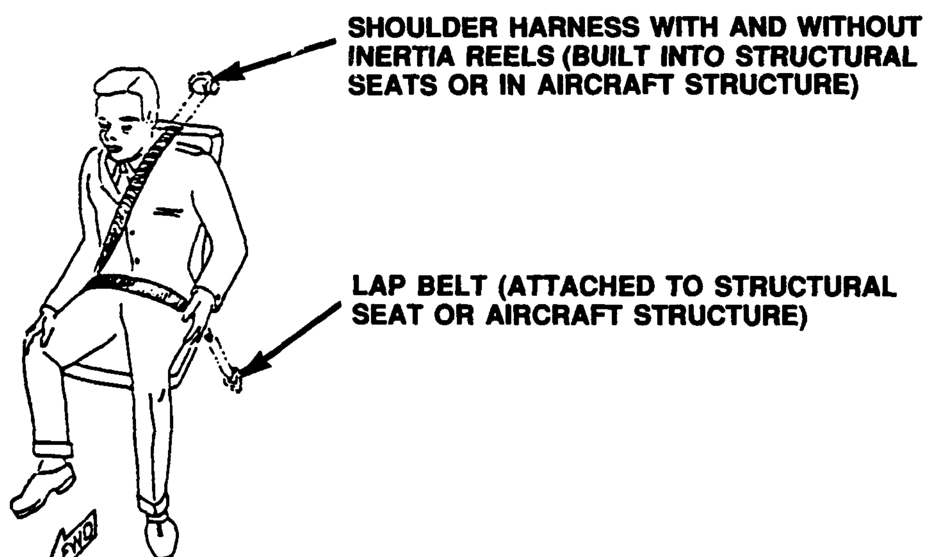


FIG. 19: GENERAL AVIATION — SINGLE SHOULDER HARNESS RESTRAINT [REF. 88]

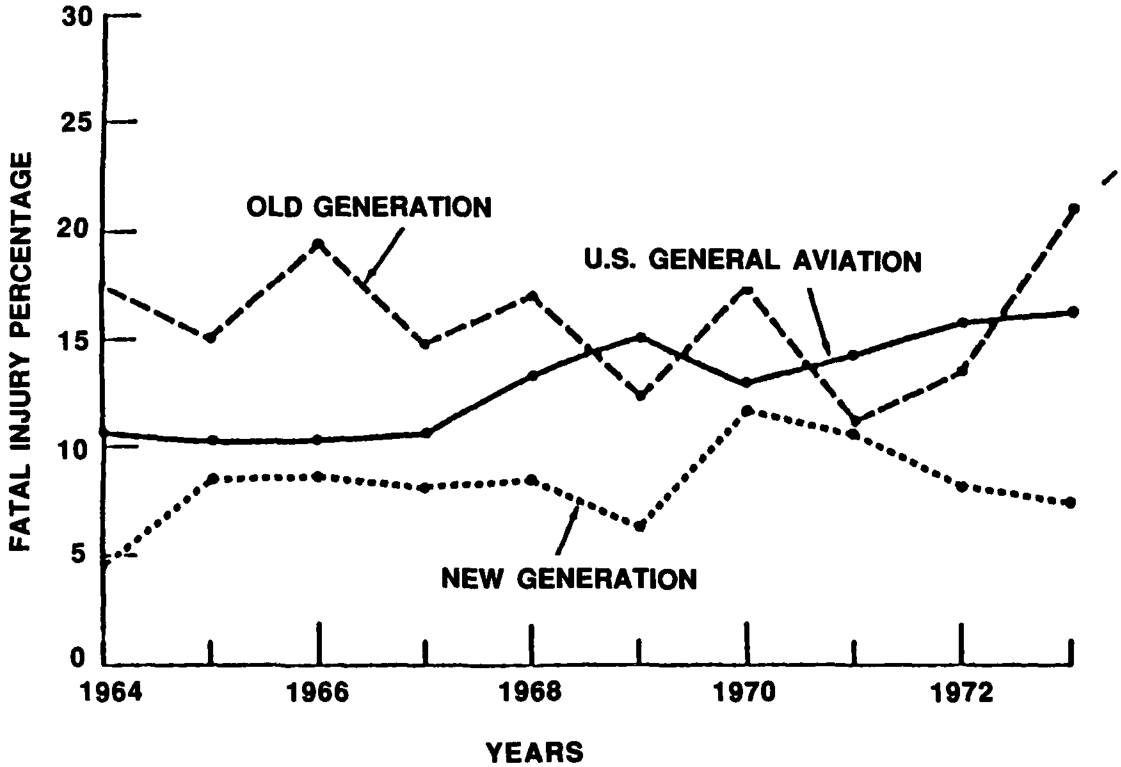
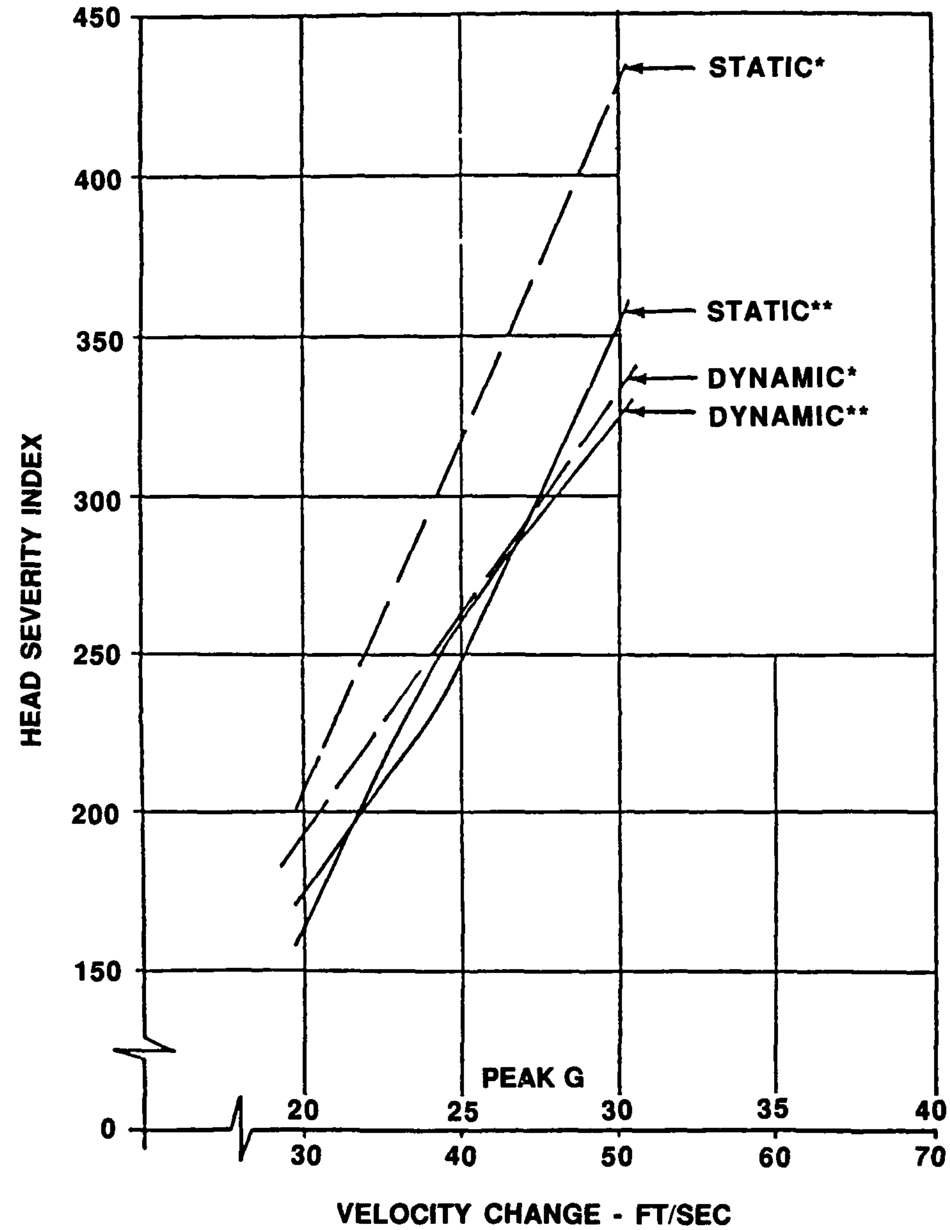


FIG. 20: FATAL INJURY EXPERIENCE IN OLD AND NEW GENERATION AERIAL APPLICATION AND U.S. GENERAL AVIATION ACCIDENTS [REF. 89]



* 1-3/4-IN. POLYESTER RESTRAINT SYSTEM
** 1-3/4-IN. NYLON RESTRAINT SYSTEM

FIG. 21: THE EFFECT OF STATIC VERSUS DYNAMIC WEBBING PROPERTIES ON THE SEVERITY INDEX FOR THE HEAD OF A 95TH PERCENTILE OCCUPANT WITH FULL GEAR UNDER VARIOUS TRIANGULAR INPUT PULSES [REF. 90]

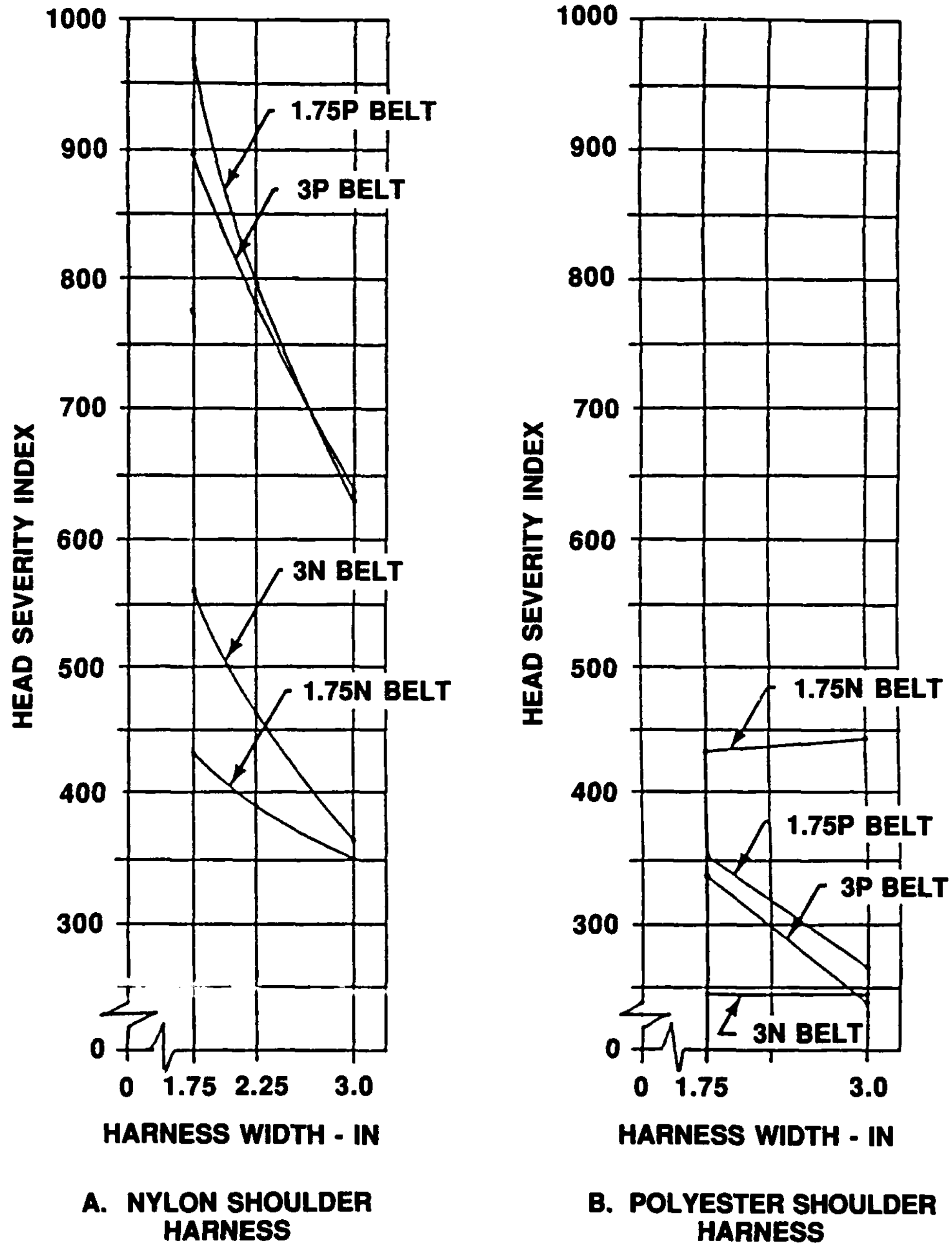


FIG. 22: HEAD SEVERITY INDEX VERSUS MATERIAL STIFFNESS, LONGITUDINAL CRASH PULSE ΔV = 50 FT/SEC, G_p = 30 AND 95TH PERCENTILE OCCUPANT EQUIPPED WITH HELMET, BODY ARMOR, AND VEST-TYPE SURVIVAL KIT [REF. 90]

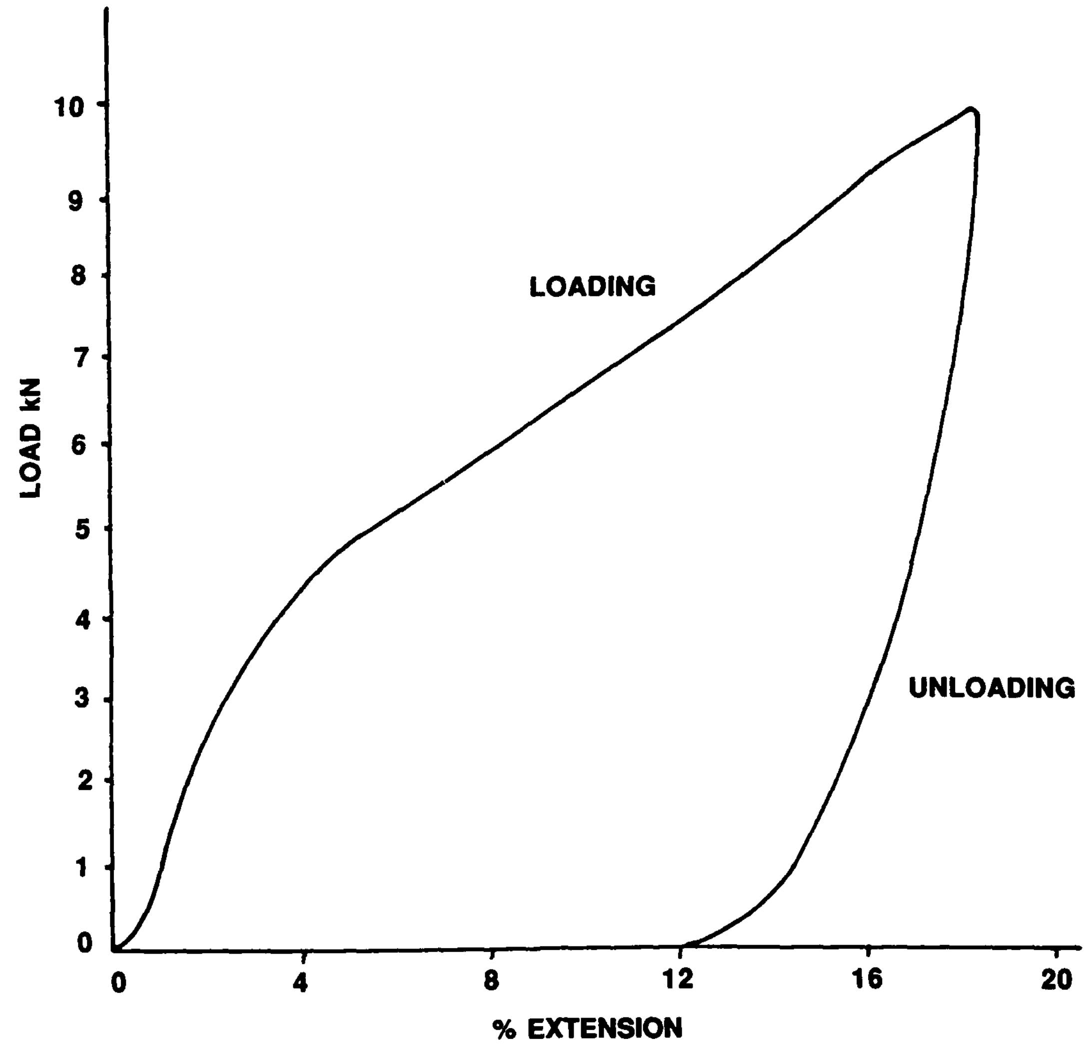


FIG. 23: LOAD Vs EXTENSION FOR SEAT BELT WEBBING [REF. 91]

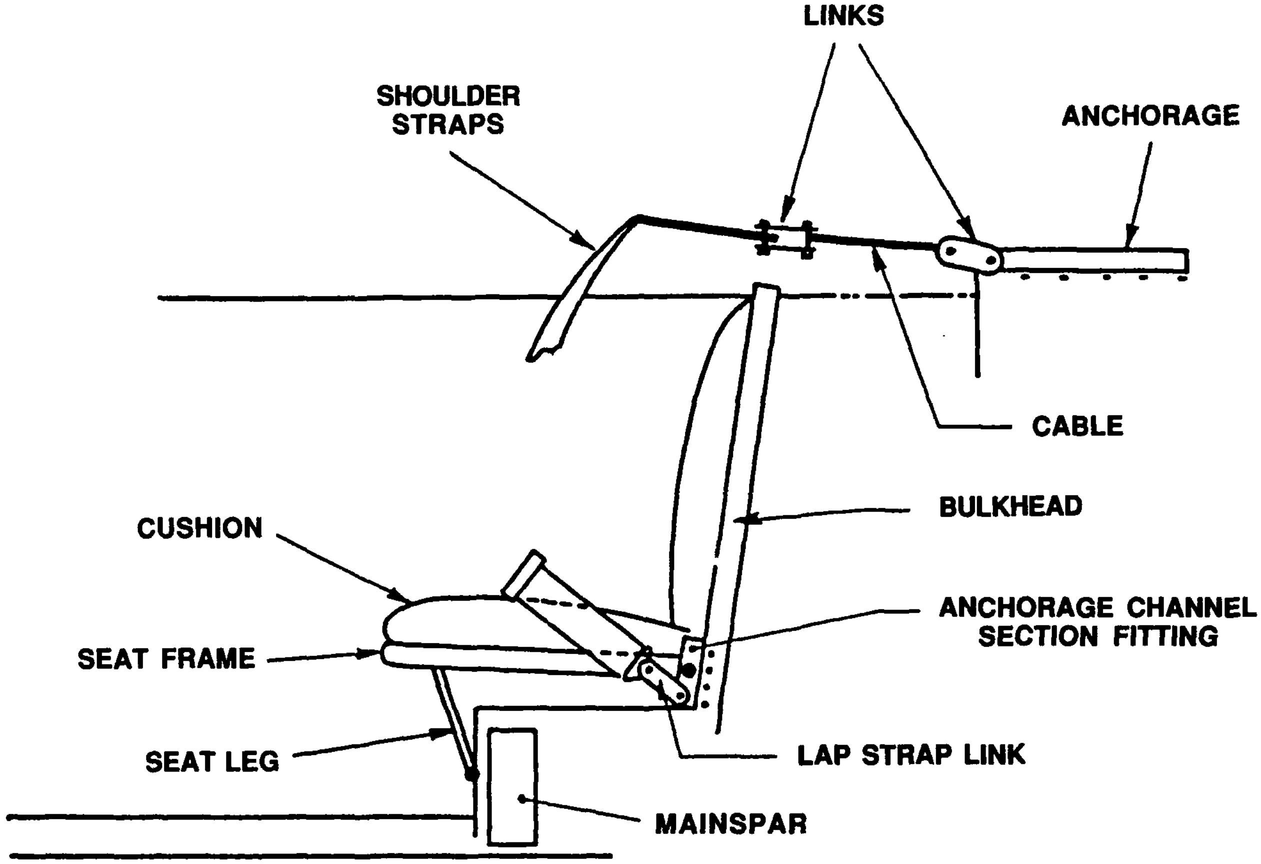


FIG. 24: LAYOUT OF SEAT AND HARNESS - AIRCRAFT "A" [REF. 95]

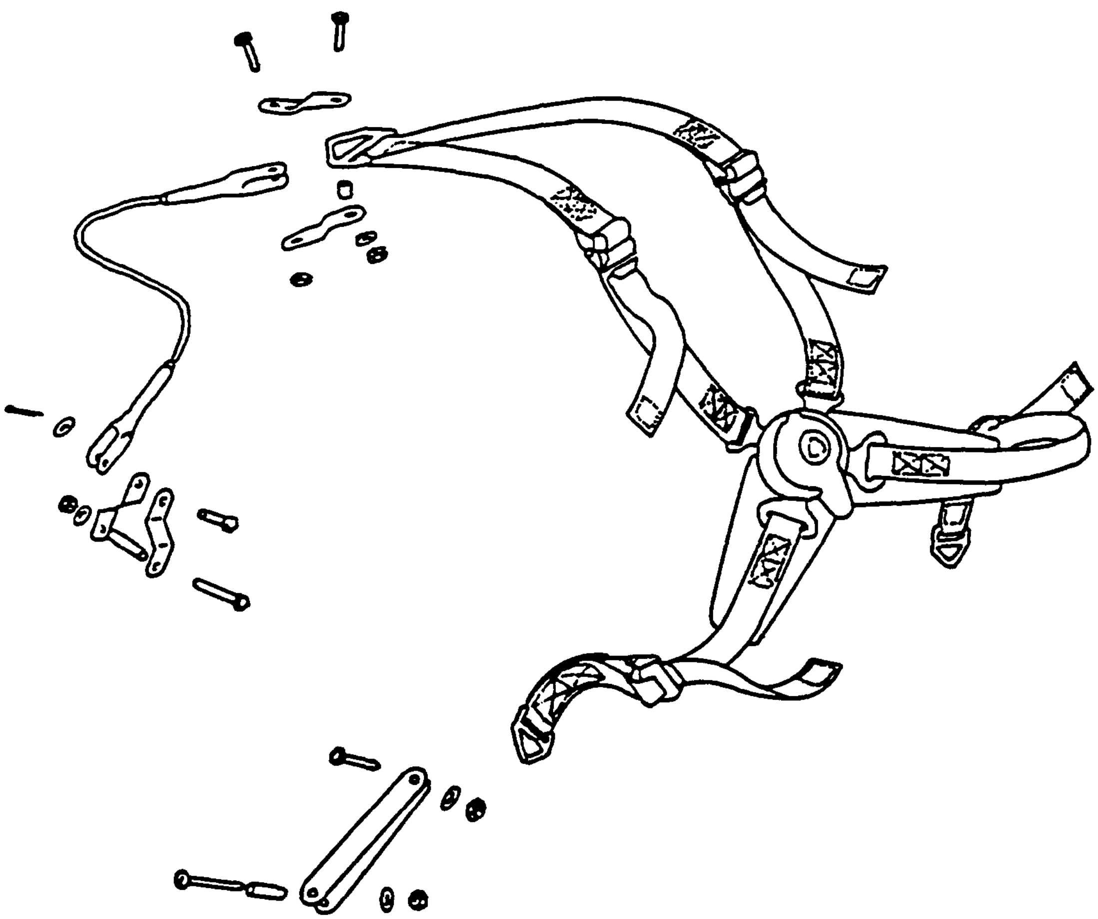


FIG. 25: RESTRAINT HARNESS AND ATTACHMENT LINKS - AIRCRAFT "A" [REF. 95]

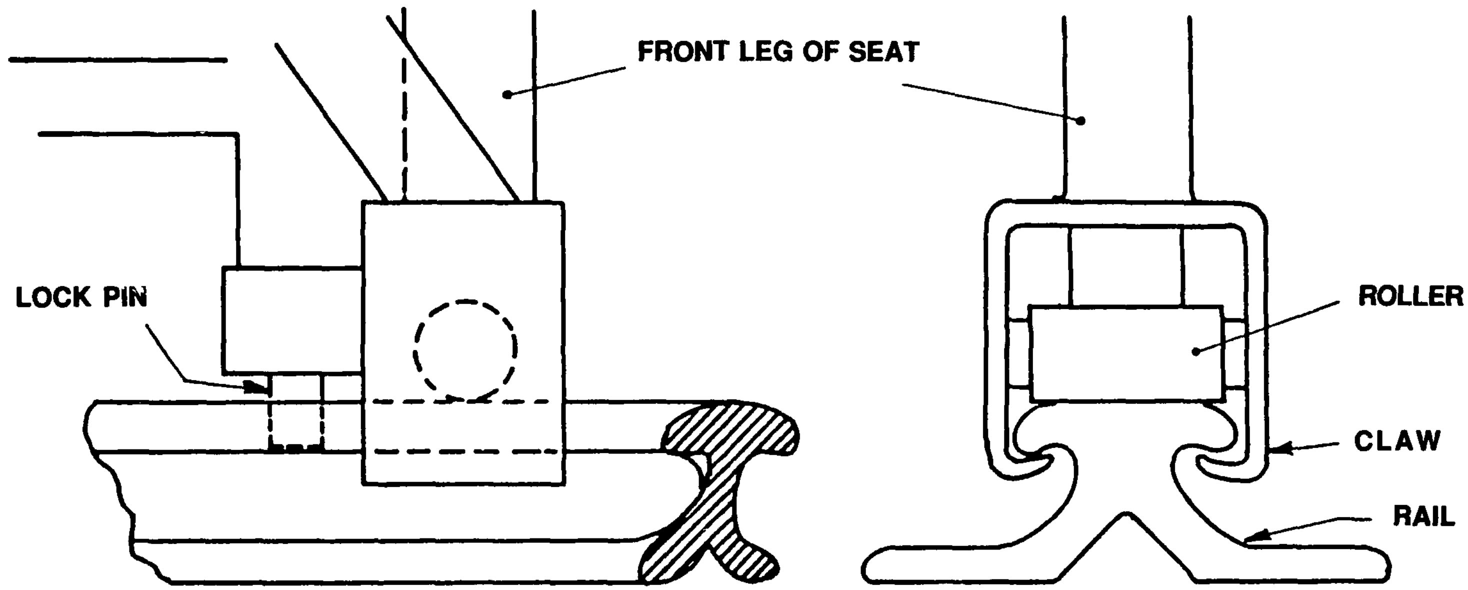


FIG. 26: ATTACHMENT OF LEGS OF FRONT SEAT TO THE RAIL - AIRCRAFT "B" (LOCK ON FRONT LEGS ONLY) [REF. 95]

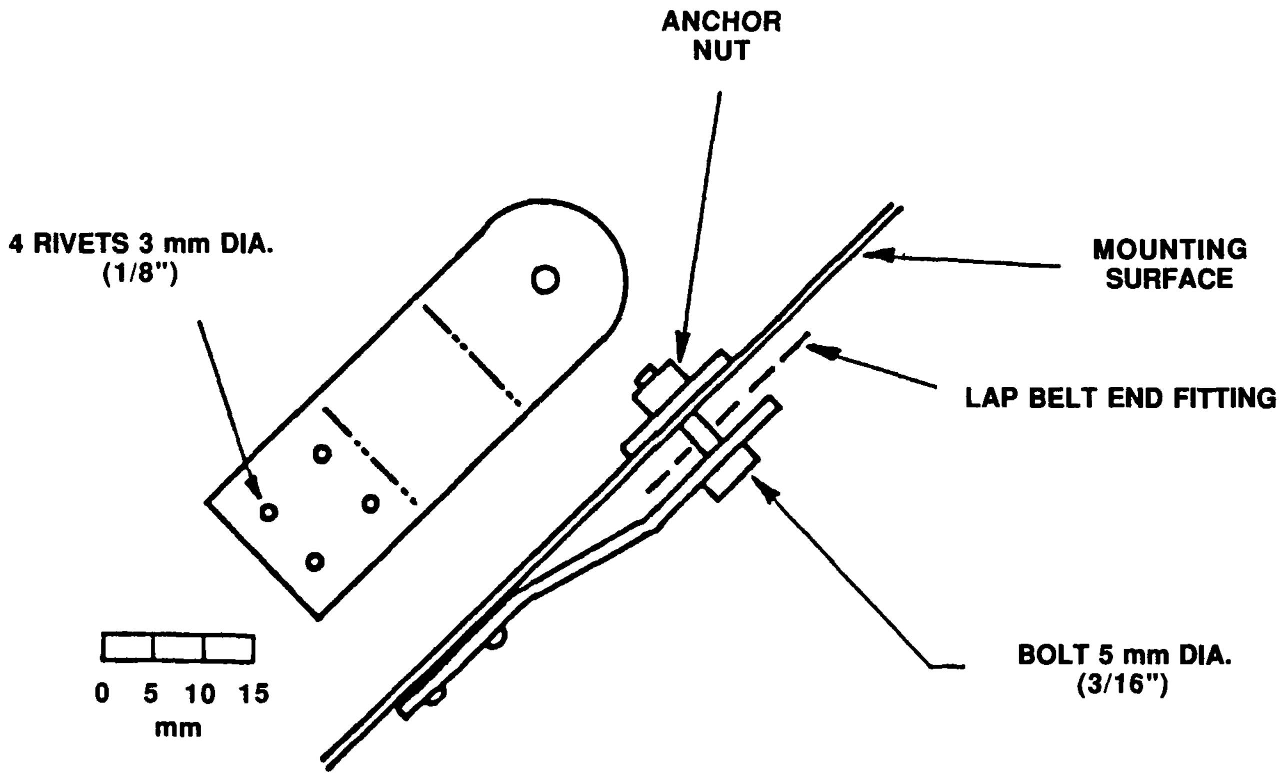


FIG. 27: LAP BELT ANCHORAGE - AIRCRAFT "B" (TO MEMBER ON FUSELAGE SIDE OR "TUNNEL") [REF. 95]

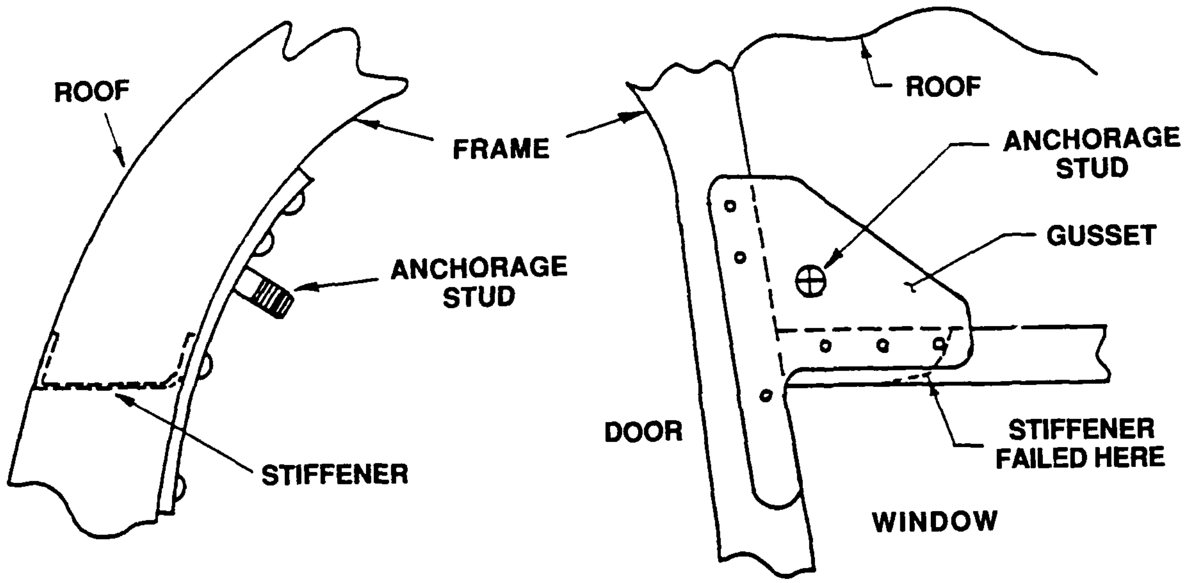


FIG. 28: SASH ANCHORAGE - AIRCRAFT "B"
[REF. 95]

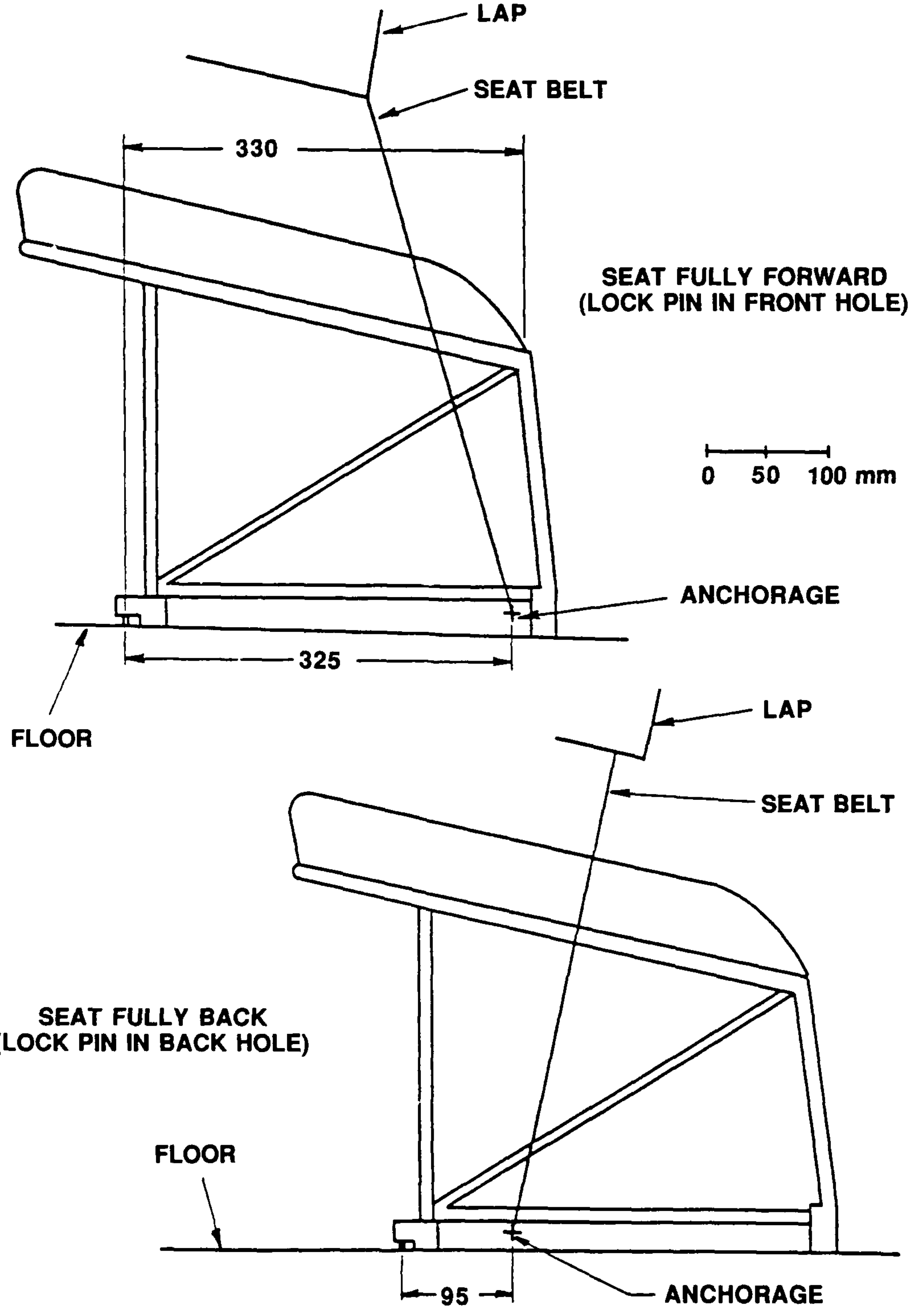


FIG. 29: LAP BELT SLOPE WITH SEAT IN FORWARD AND FULLY BACK SEATING POSITIONS FOR AIRCRAFT "C" [REF. 95]

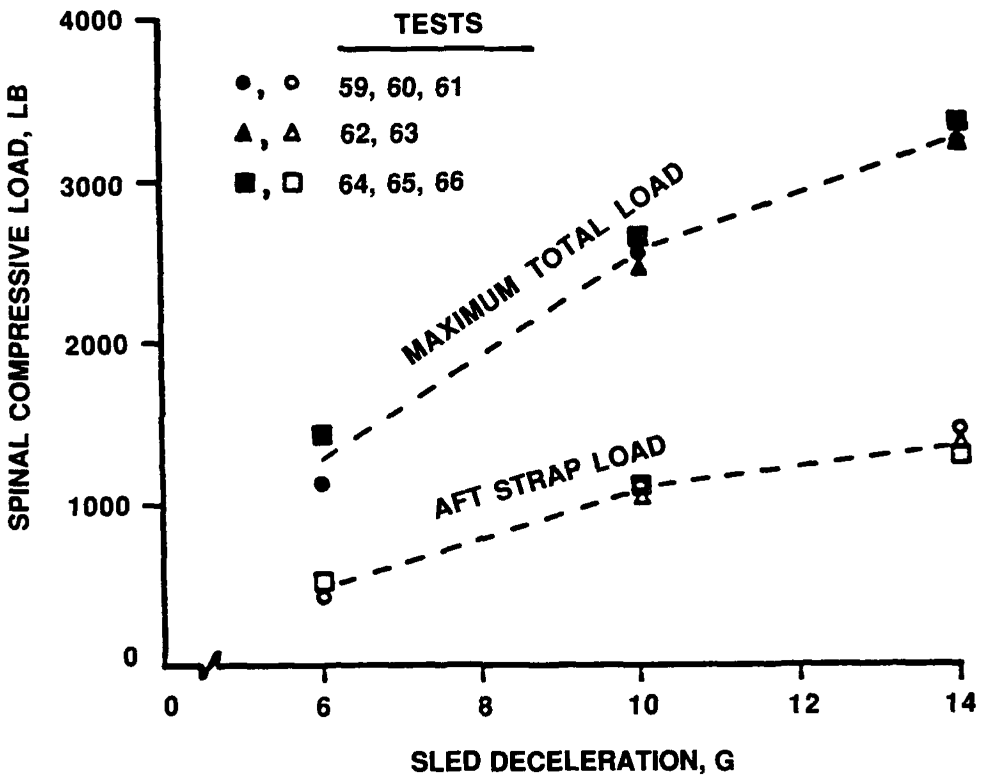
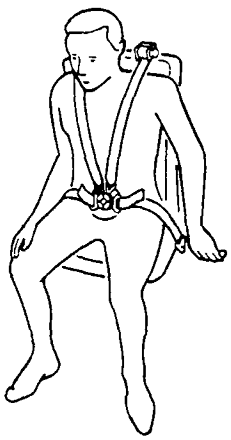
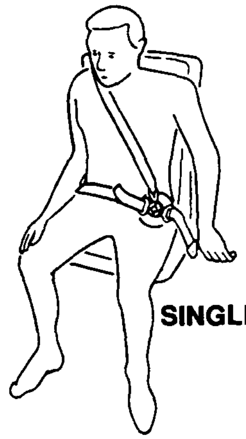


FIG. 30: RESULTS OF COMPUTATIONS OF TEST RESULTS [REF. 96]

AIRCRAFT TORSO RESTRAINT SYSTEM
(APPLICABLE TO DUAL AND SINGLE TYPES)





SINGLE

- **LOAD**
  - **STRENGTH**
  - **ELONGATION**

- **PERFORMANCE**
  - WEBBING: ABRASION
  - TILT-LOCK: MOTION
  - RETRACTOR
    - LOCK: 5,000 CYCLES
    - FUNCTION: 25,000 CYCLES
  - BUCKLE: 10,210 CYCLES
  - ADJUSTER: SLIP

- **ENVIRONMENT**
  - SOLVENTS
  - FLAME: FEDERAL TEST METHOD STANDARD 191 METHOD 5906 △3
  - TEMPERATURE: ASTM D-756-78 PROCEDURE D △2
  - CORROSION: ASTM B-117-73 △2
  - COLOR-FASTNESS
    - CROCKING (RUBBING): AATCC 8-1981 △1
    - STAINING: AATCC 107-1981 △1
  - LIGHT: ASTM G-23-81 △2

△1 PUBLISHED BY THE AMERICAN ASSOCIATION OF TEXTILE CHEMISTS AND COLORISTS, P.O. BOX 12215, RESEARCH TRIANGLE PARK, N.C. 27709

△2 PUBLISHED BY THE AMERICAN SOCIETY FOR TESTING AND MATERIALS, 1916 RACE STREET, PHILADELPHIA, PA 19103

△3 PUBLISHED BY THE COMMANDING OFFICER, NAVAL PUBLICATIONS AND FORMS CENTER, 5801 TABOR AVENUE, PHILADELPHIA, PA 19120

FIG. 31: TESTS [REF. 100]

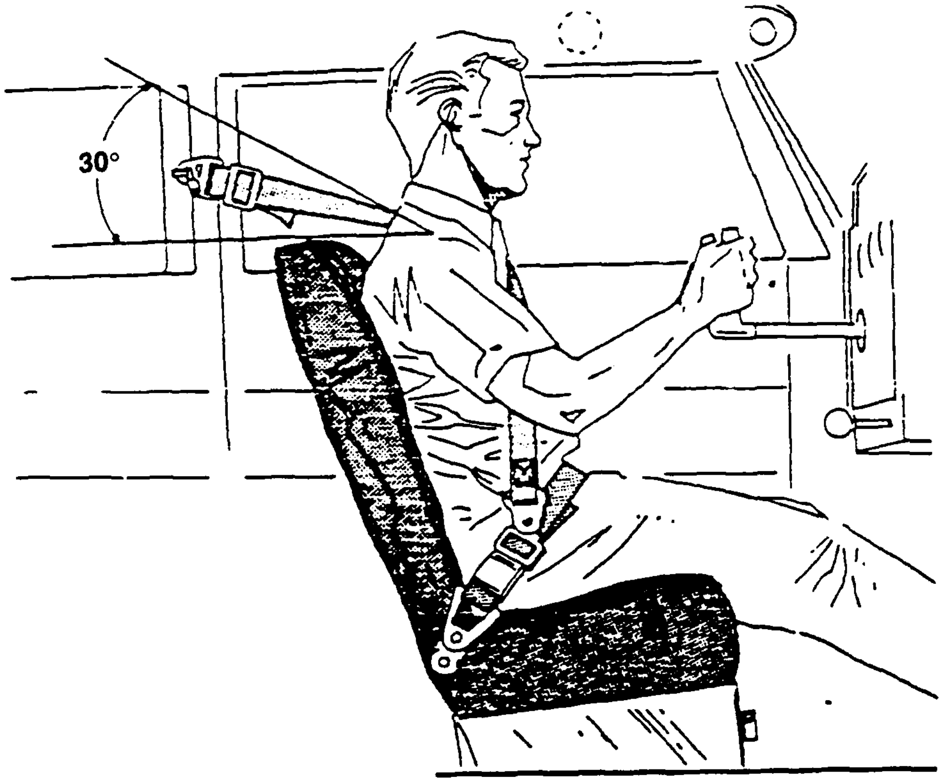


FIG. 32: SIDE MOUNTED - SINGLE DIAGONAL TYPE HARNESS [REF. 102]

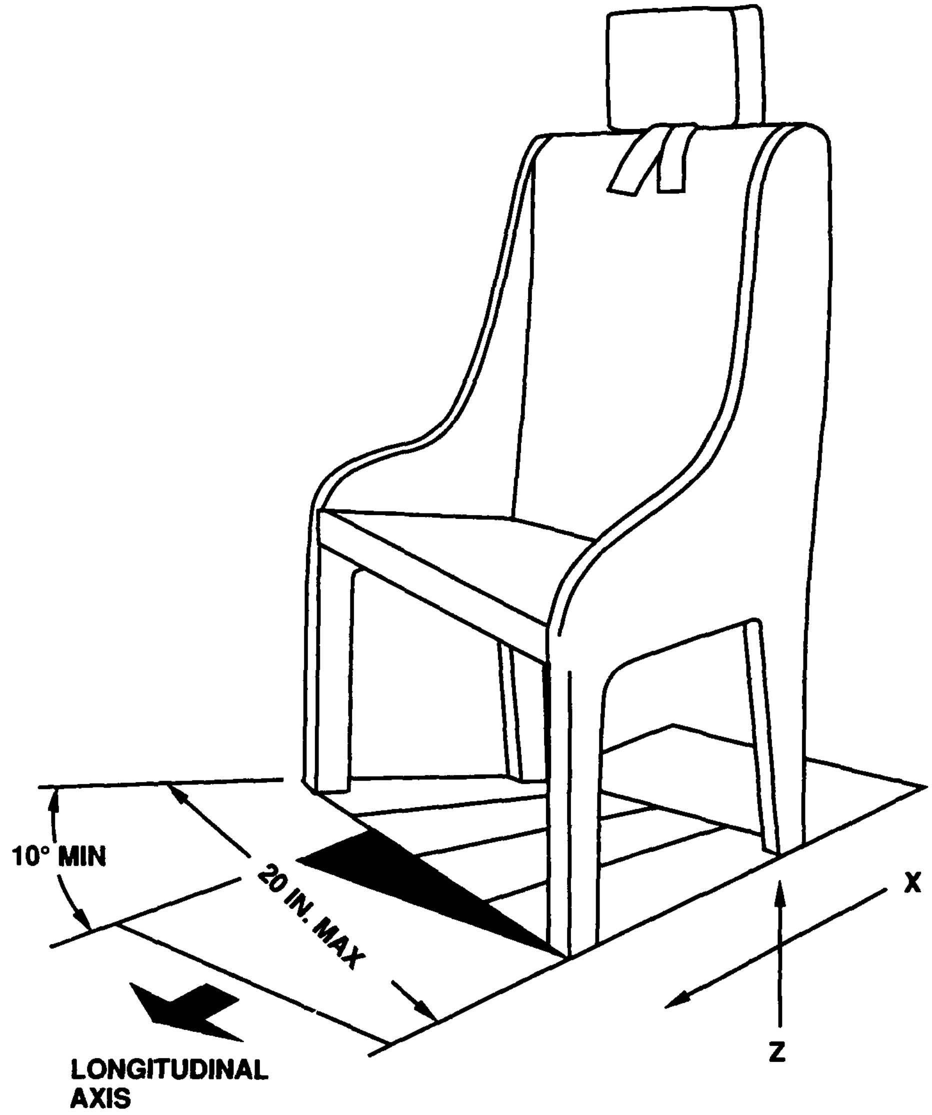


FIG. 33: SKETCH ILLUSTRATING FLOOR WARPAGE REQUIREMENT NECESSARY TO INSURE SEAT RETENTION IN CRASHES [REF. 58]

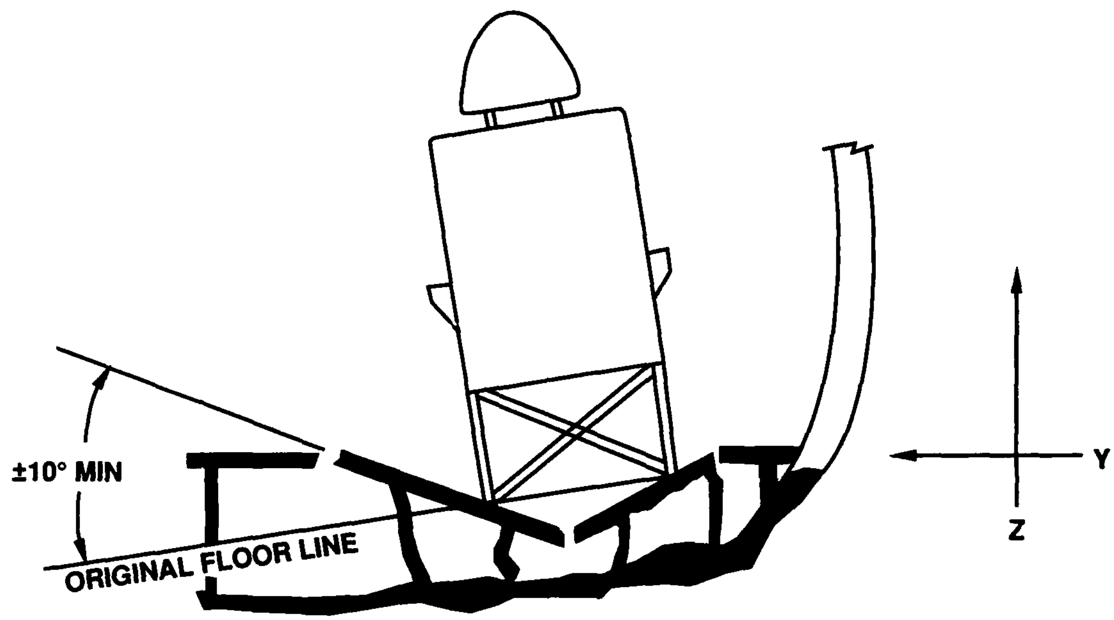


FIG. 34: SKETCH ILLUSTRATING BUCKLING OR "DISHING" DEFORMATION REQUIRED TO INSURE SEAT RETENTION IN SEVERE CRASHES (VIEW LOOKING ALONG LONGITUDINAL X-AXIS OF AIRCRAFT) [REF. 58]

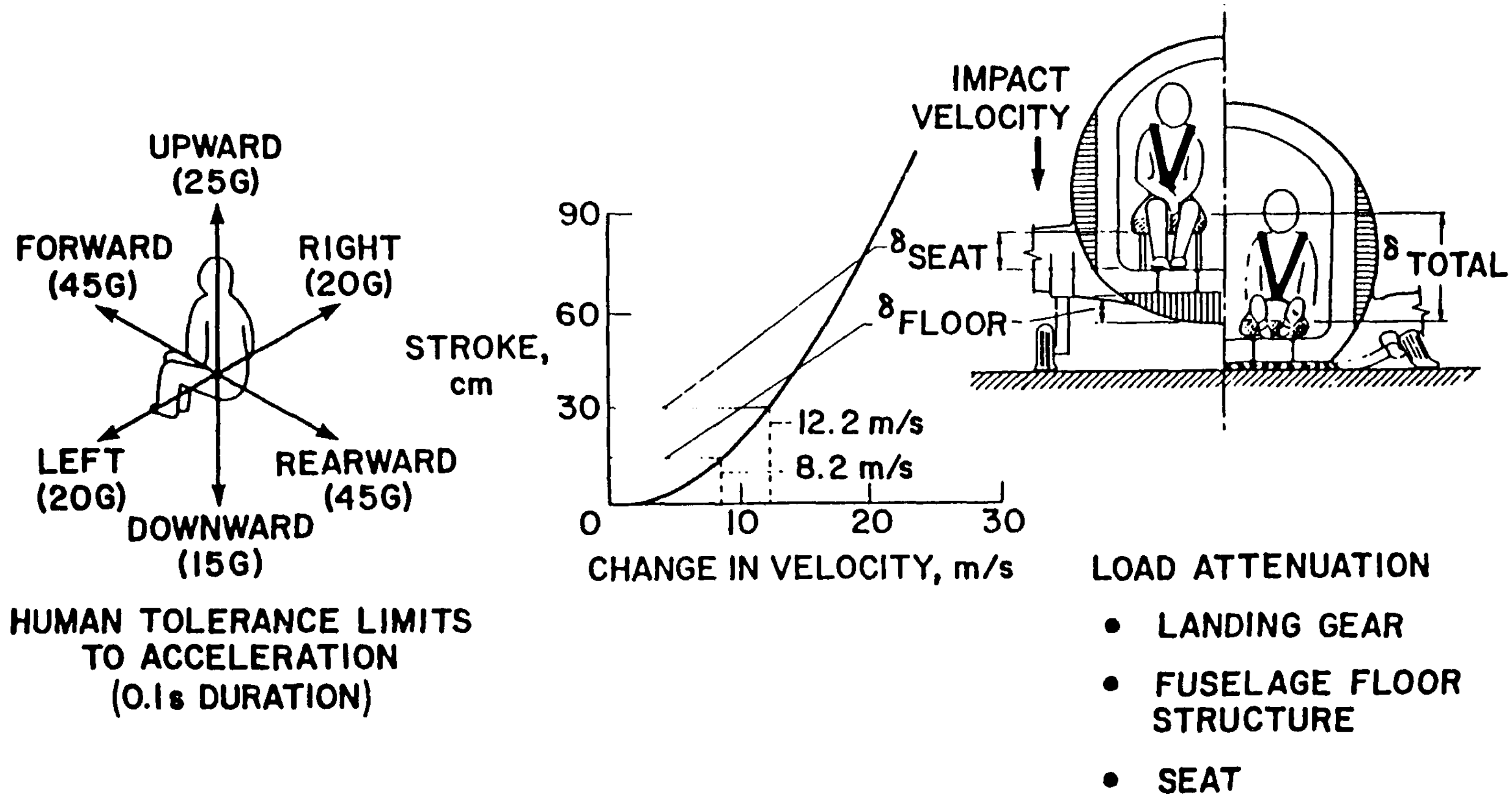
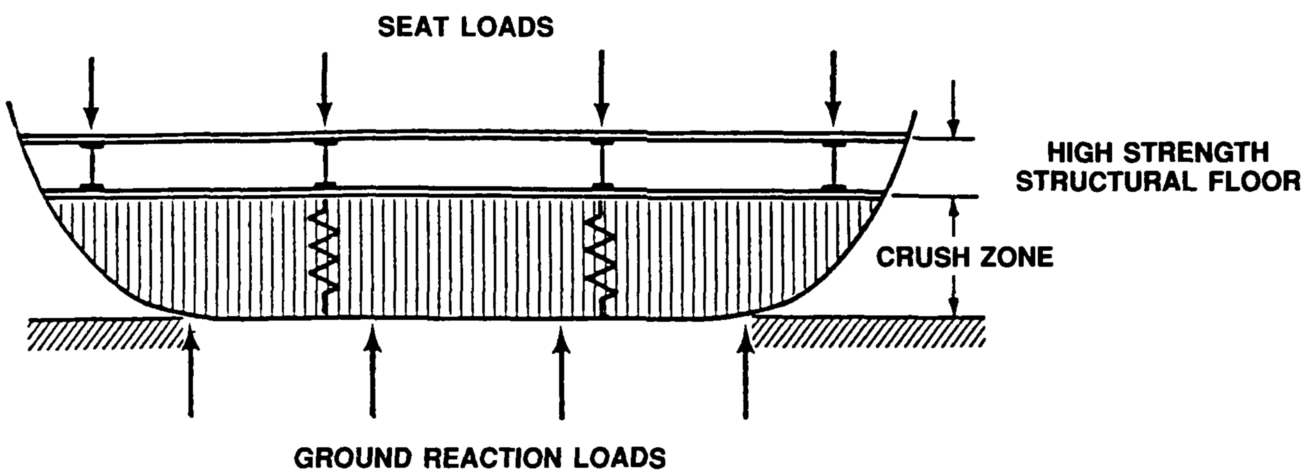
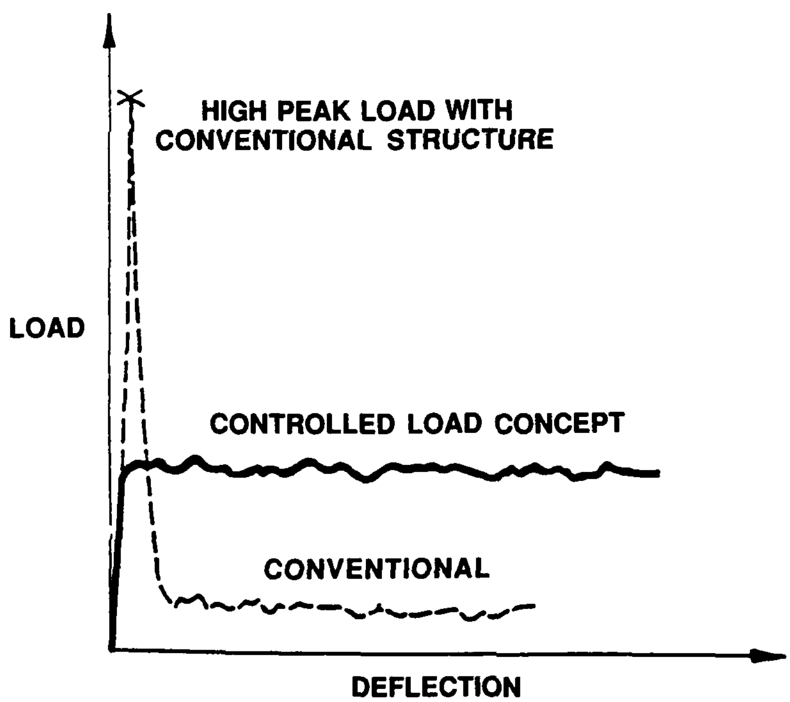


FIG. 35: STROKE POTENTIALLY AVAILABLE IN TYPICAL GENERAL AVIATION AIRCRAFT FOR ENERGY DISSIPATION DURING A CRASH [REF. 105]





<u>CRUSH ZONE LOAD-DEFLECTION CHARACTERISTICS</u>

FIG. 36: LOWER FUSELAGE DESIGN PHILOSOPHY [REF. 107]

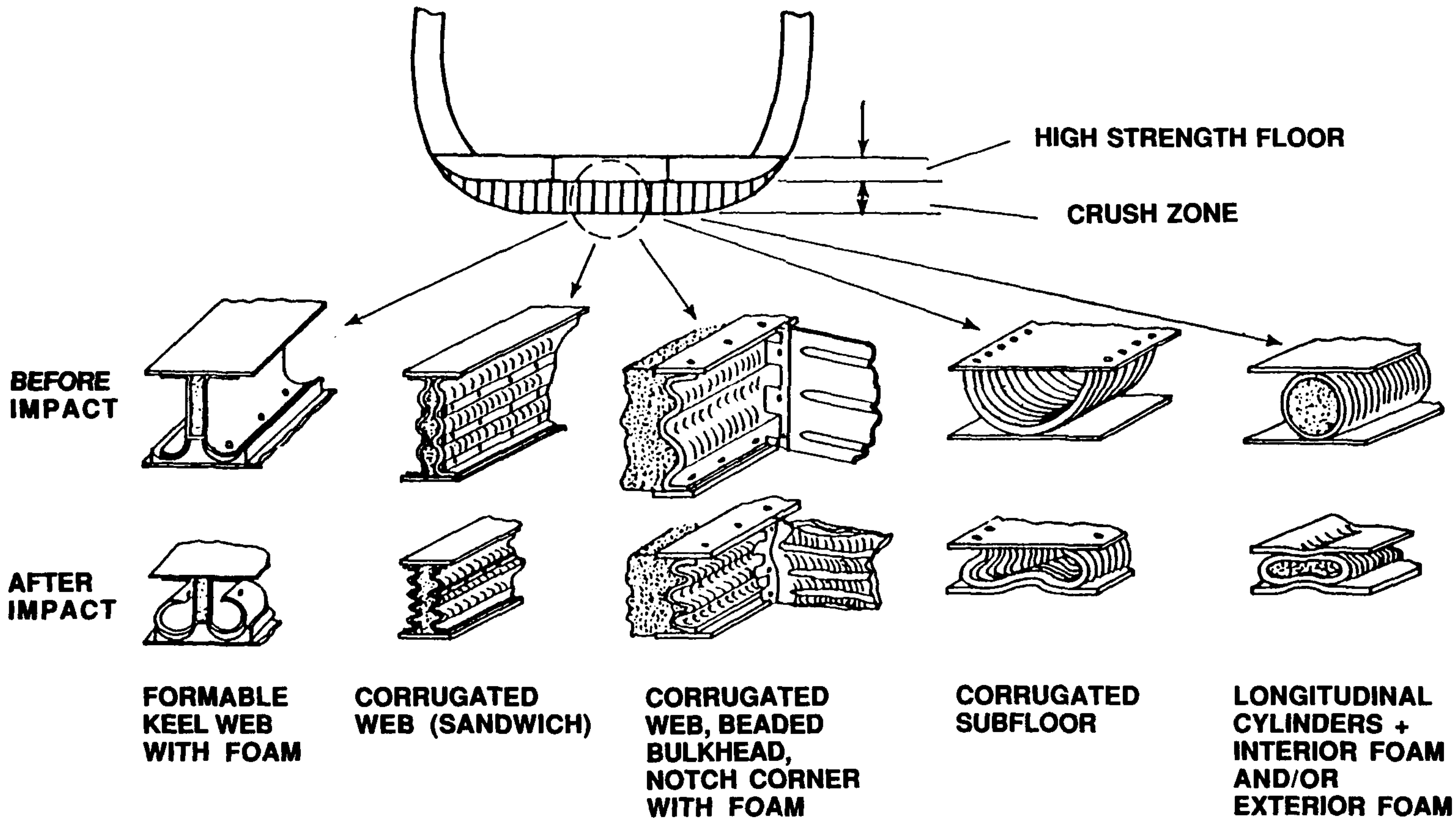


FIG. 37: LOWER FUSELAGE LOAD-LIMITING, ENERGY ABSORBING CONCEPTS [REF. 107]

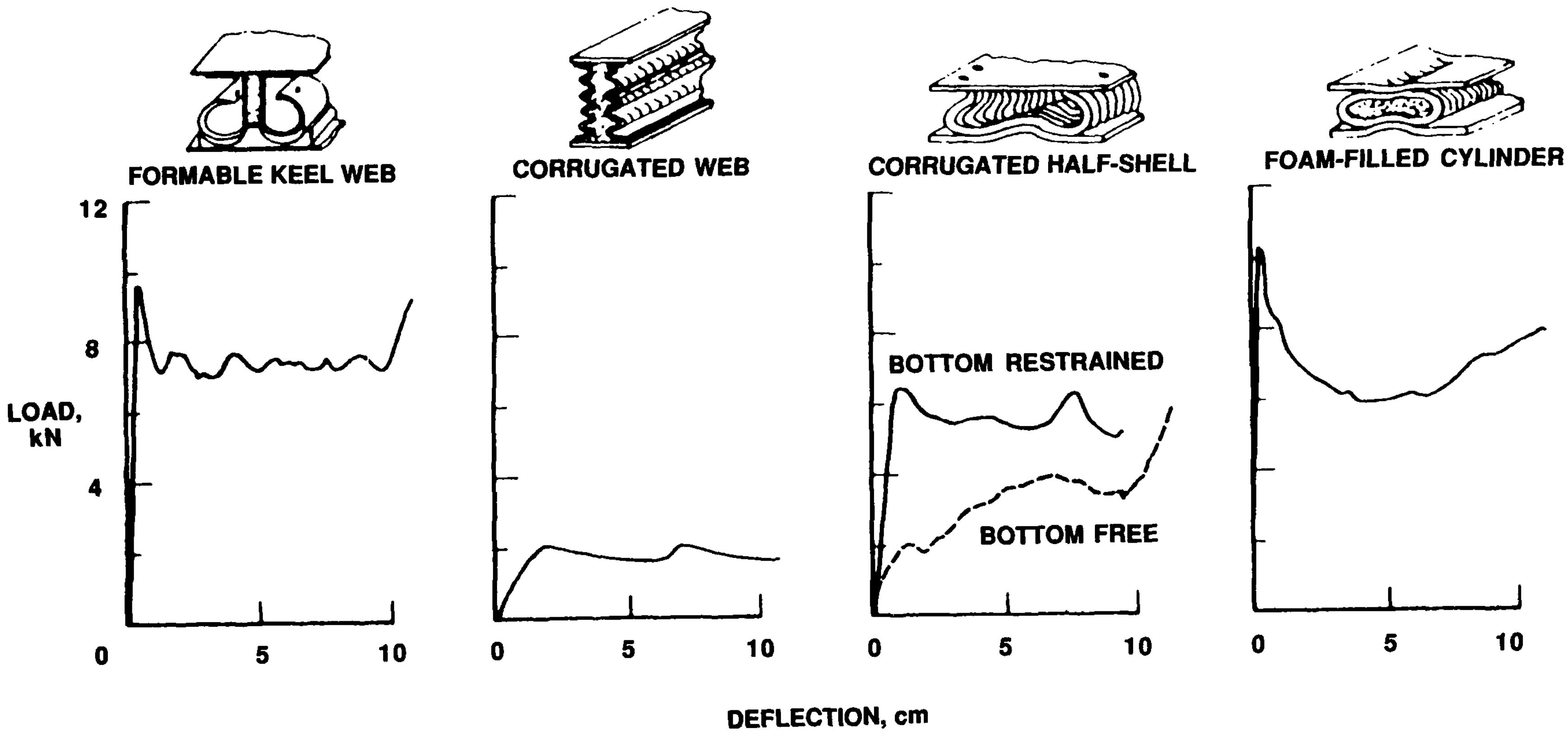


FIG. 38: SAMPLES OF LOAD-DEFLECTION CURVES FROM DESIGN SUPPORT TESTS [REF. 107]

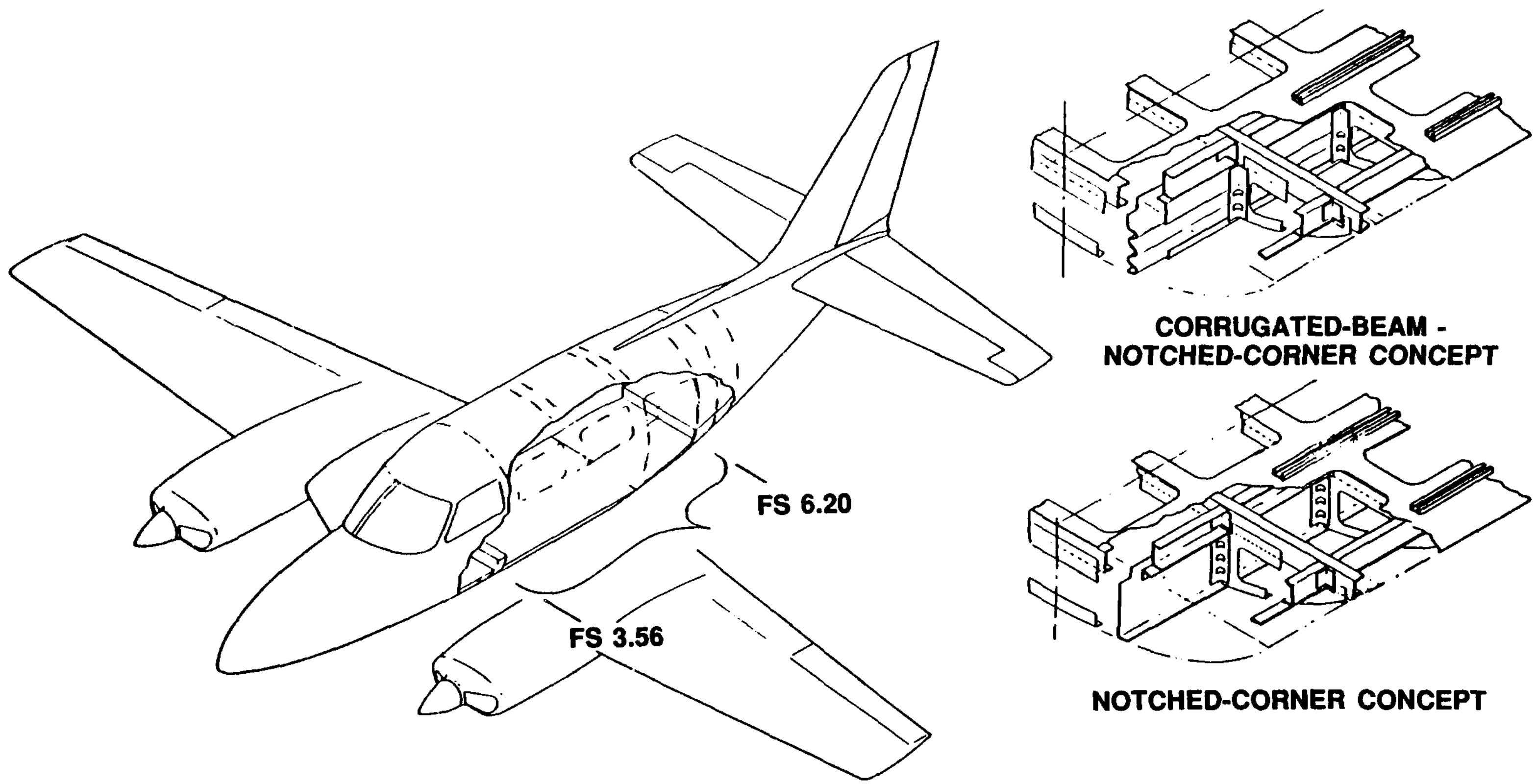


FIG. 39: FUSELAGE MODIFICATION SCHEMATIC [REF. 108]
DIMENSIONS ARE IN METERS

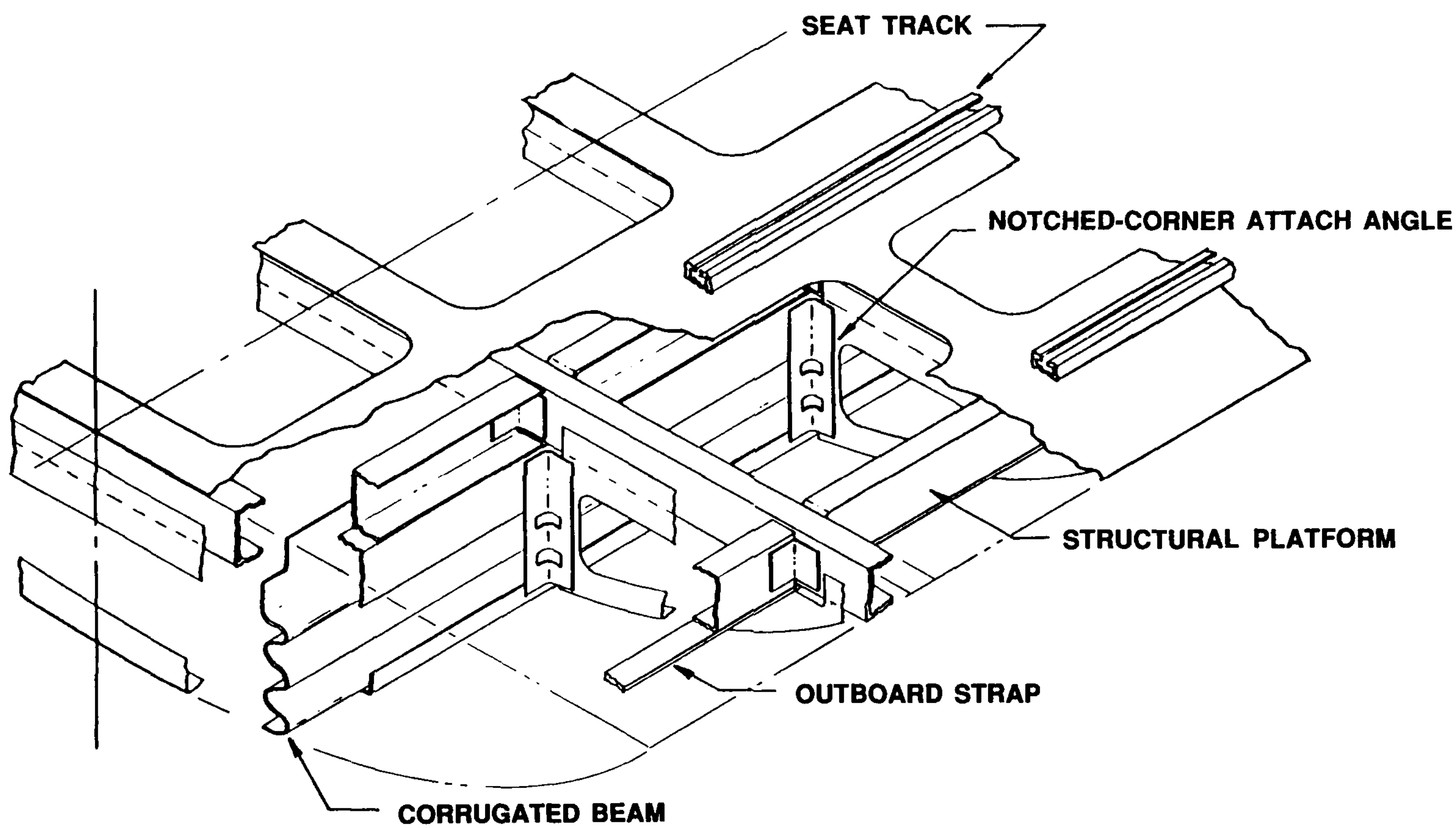


FIG. 40: FUSELAGE MODIFICATION DETAIL OF CORRUGATED-BEAM - NOTCHED-CORNER STRUCTURE [REF. 108]

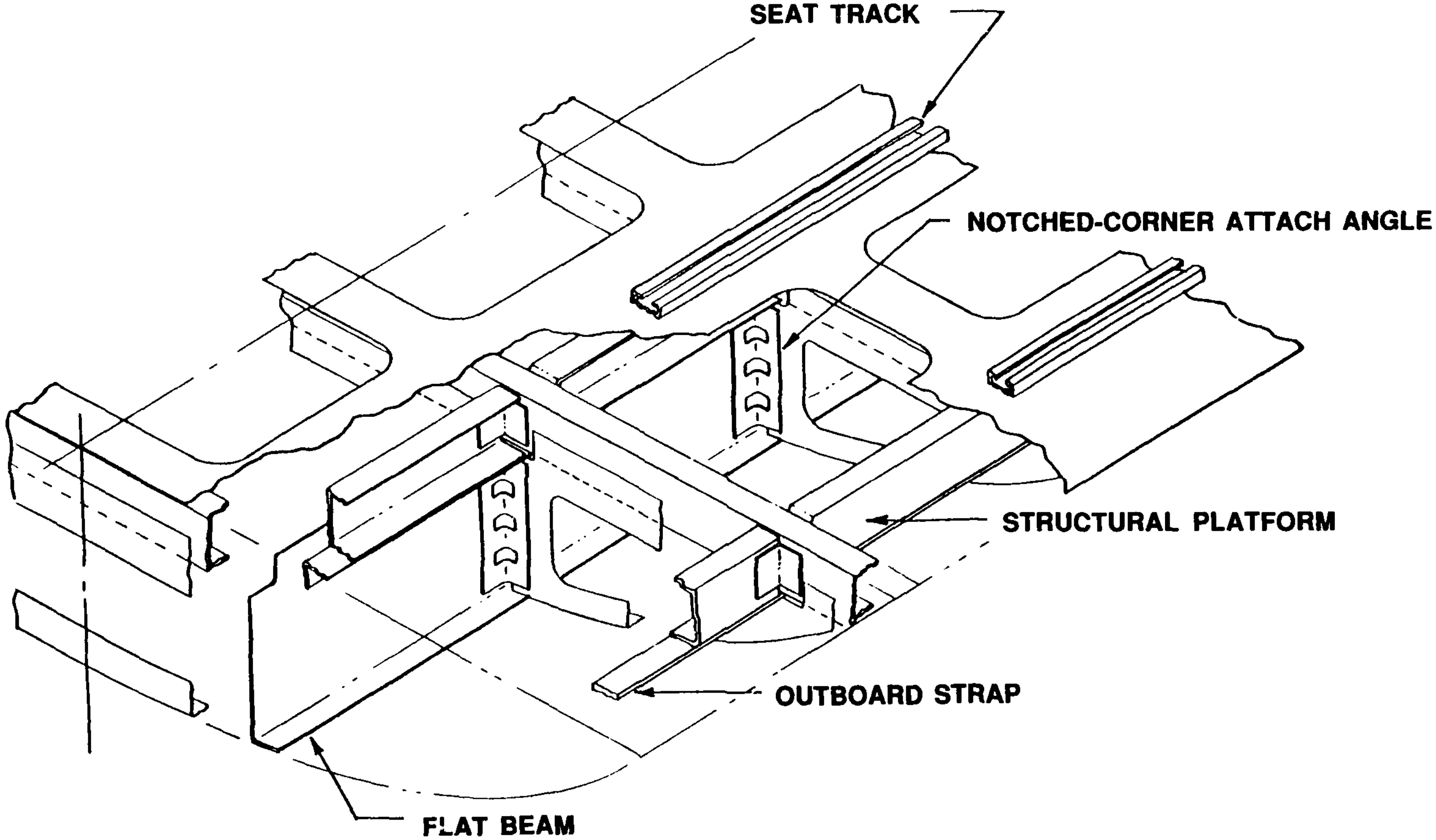


FIG. 41: FUSELAGE MODIFICATION DETAIL OF NOTCHED-CORNER STRUCTURE [REF. 108]

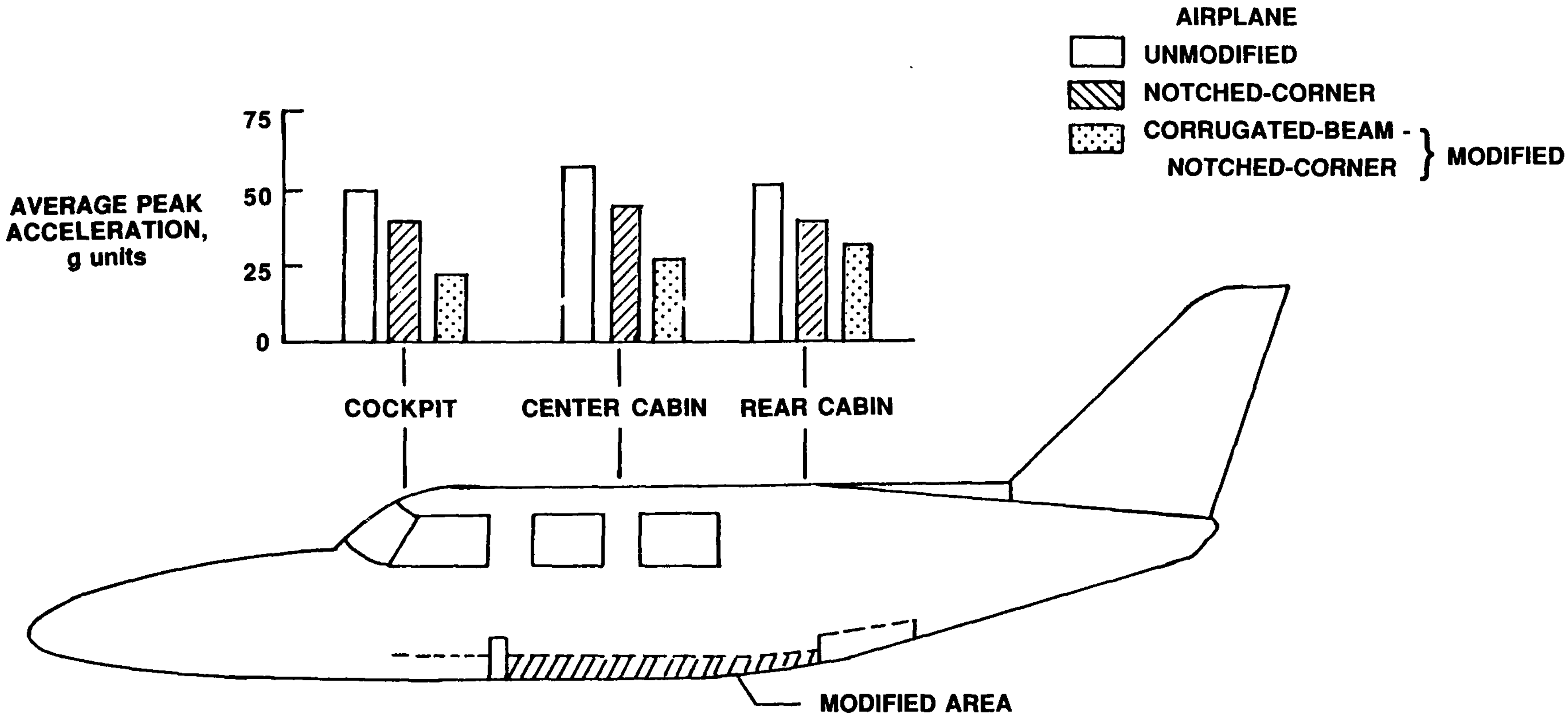


FIG. 42: AVERAGE PEAK NORMAL FLOOR ACCELERATIONS AT THREE AIRPLANE LOCATIONS [REF. 108]

Appendix A

Text of General Aviation Safety Panel's Recommendations

Dynamic Testing of Seats

Recommended seat criteria for small general aviation aircraft applying for initial type certification after December 31, 1985 for operations with fewer than 10 passenger seats.

(a) Each seat, bench or other device for crew or passenger occupancy must successfully complete dynamic tests with an occupant weight of 170 pounds in accordance with each of the conditions stated below:

(1) A change of velocity of not less than 31 feet per second when the seat, bench or other seating device is oriented in its nominal position with respect to the aircraft's reference system and the aircraft's longitudinal axis is canted upward 60 degrees with respect to the impact velocity vector and the aircraft's lateral axis is perpendicular to a vertical plane containing the impact velocity vector and the aircraft's longitudinal axis. For the aircraft's first row of seats, peak deceleration must occur in not more than .05 seconds after impact and must reach a minimum of 19 g's. For all other seats, peak deceleration must occur in not more than .06 seconds after impact and must reach a minimum of 15 g's.

(2) A change in velocity of not less than 42 feet per second when the seat, bench or other seating device is oriented in its nominal position with respect to the aircraft's reference system and the aircraft's longitudinal axis is yawed 10 degrees either right or left of the impact velocity vector (but in such a way as to cause the greatest load on the upper torso restraint system), the aircraft's lateral axis is contained in a horizontal plane containing the impact velocity vector and the aircraft's vertical axis is perpendicular to a horizontal plane containing the impact velocity vector. For the aircraft's first row of seats, peak deceleration must occur in not more than .05 seconds after impact and must reach a minimum of 26 g's. For all other seats, peak deceleration must occur in not more than .06 seconds after impact and must reach a minimum of 21 g's. (Note: The aircraft's reference system is defined as consisting of three mutually perpendicular axes where the vertical axis is perpendicular to a water line reference system of the aircraft and parallel to the station reference system and the longitudinal axis is perpendicular to the station reference system. The velocity change shall be pure translation with no angular acceleration considered.)

(3) The floor rails used to attach the seating device to the airframe must be misaligned with respect to each other by at least 10 degrees vertically (i.e. out of parallel), with the direction at the option of the manufacturer, to account for floor warp.

(4) Dynamic tests in accordance with the conditions stated in paragraph (a), subparagraphs (1), (2) and (3) are considered to be successfully completed when the performance measures (4a) through (4f) are demonstrated.

(4a) Loads in individual upper torso straps do not exceed 1,750 pounds. If dual straps are used for retaining the upper torso, the total strap loads do not exceed 2,000 pounds.

(4b) The maximum pelvic load as measured in a 49 CRF 572 dummy does not exceed 1,500 pounds.

(4c) The occupant's upper torso strap or straps remain on or in the immediate vicinity of the occupant's shoulder during the impact.

(4d) The lap belt remains on the occupant's pelvis during the impact.

(4e) The occupant's head either does not contact any portion of the cockpit or cabin or if it does, the head impact does not exceed a Head Impact Criteria (HIC) of 1,000, as determined by the test procedures defined in SAE J921.

(4f) The attachment between the seating device and the aircraft's structure remains intact (although the structure can have exceeded its limit load)

and the restraint system remains intact (although it also can have experienced separation that is intended as part of its design) as long as the conditions contained in (4a), (4b), (4c), (4d) and (4e) are met.

(b) In addition to the dynamic tests and criteria defined in paragraph (a) and its subparagraphs (1) through (4f), all seats, benches or other seating devices and its supporting structure must be designed to withstand the static load imposed by a 215 pound occupant when subject to the aircraft's design loads as defined in the aircraft's approved flight/ground envelope.

(c) Paragraphs (a) and (b) above specify a minimum standard for new aircraft with application for type certification dated after December 31, 1985. An applicant for a type certificate has the option to depart from the criteria presented in paragraphs (a) and (b) above provided an alternate approach that achieves the same or equivalent level of occupant crash tolerance can be substantiated on a rational basis.

Mandatory Equipage of Shoulder Harnesses

The General Aviation Safety Panel affirms its earlier recommendation that all FAR Part 23 general aviation aircraft manufactured after December 31, 1984 be equipped with upper torso restraint systems. We further recommend that the FAA consider ways to facilitate the installation of upper torso restraint systems in older general aviation aircraft, and that the FAA work with the SAE Upper Torso Restraint Committee to formulate acceptable standards for harness material and attachments to be used in aircraft manufactured after December 31, 1985.

Appendix B Part 23.562

Emergency Landing Dynamic Conditions

(a) Each seat/restraint system for use in a normal, utility, or acrobatic category airplane must be designed to protect each occupant during an emergency landing when-
   (1) Proper use is made of seats, safety belts, and shoulder harnesses provided for in the design and
   (2) The occupant is exposed to the loads resulting from the conditions prescribed in this section.

(b) Each seat/restraint system, for crew or passenger occupancy in a normal, utility, or acrobatic category airplane, must successfully complete dynamic tests or be demonstrated by rational analysis supported by dynamic tests, in accordance with each of the following conditions. These tests must be conducted with an occupant simulated by an anthropomorphic test dummy (ATD) defined by 49 CFR Part 572, Subpart B, or an FAA approved equivalent, with a nominal weight of 170 pounds and seated in the normal upright position.
   (1) For the first test, the change in velocity may not be less than 31 feet per second. The seat/restraint system must be oriented in its nominal position with respect to the airplane and with the horizontal plane of the airplane pitched up 60 degrees, with no yaw, relative to the impact vector. For seat/restraint systems to be installed in the first row of the airplane, peak deceleration must occur in not more than .05 seconds after impact and must reach a minimum of 19 g.
   (2) For all other seat/restraint systems, peak deceleration must occur in not more than 0.06 seconds after impact and must reach
a minimum of 15 g.
   (3) For the second test, the change in velocity may not be less than 42 feet per second. The seat/restraint system must be oriented in its nominal position with respect to the airplane and with the vertical plane of the airplane yawed 10 degrees, with no pitch, relative to the impact vector in a direction that results in the greatest load on the shoulder harness. For seat/restraint systems to be installed in the first row of the airplane, peak deceleration must occur in not more than .05 seconds after impact and must reach a minimum of 26 g. For all other seat/restraint systems, peak deceleration must occur in not more than .06 seconds after impact and must reach a minimum of 21 g.
   (3) To account for floor warpage, the floor rails or attachment devices used to attach the seat/restraint system to the airframe structure must be preloaded to misalign with respect to each other by at least 10 degrees vertically (i.e. pitch out of parallel) and one of the rails or attachment devices must be preloaded to misalign by 10 degrees in roll prior to conducting the test defined by paragraph (b)(2) of this section.

(c) Compliance with the following requirements must be shown during the dynamic tests conducted in accordance with paragraph (b) of this section:
   (1) The seat/restraint system must restrain the ATD although seat/restraint system components may experience deformation, elongation, displacement, or crushing intended as part of the design.
   (2) The attachment between the seat/restraint system and the test fixture must remain intact, although the seat structure may have deformed.
   (3) Each shoulder harness strap must remain on the ATD's shoulder during the impact.,
   (4) The safety belt must remain on the ATD's pelvis during the impact.
   (5) The results of the dynamic tests must show that the occupant is protected from serious head injury.
      (i) When contact with adjacent seats, structure, or other items in the cabin can occur, protection must be provided so that the head impact does not exceed a head injury criteria (HIC) of 1,000.
      (ii) The value of HIC is defined as-

$$HIC = \left\{ (t_2 - t_1) \left[\frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a(t)dt \right]^{2.5} \right\}_{max}$$

Where t_1 is the initial integration time, expressed in seconds, t_2 is the final integration time, expressed in seconds, $(t_2 - t_1)$ is the time duration of the major head impact, expressed in seconds, and a(t) is the resultant deceleration at the center of gravity of the head form expressed as a multiple of g (units of gravity).

(iii) Compliance with the HIC limit must be demonstrated by measuring the head impact during dynamic testing as prescribed in paragraphs (b)(1) and (b)(2) of this section or by a separate showing of compliance with the head injury criteria using test or analysis procedures.

(6) Loads in individual shoulder harness straps may not exceed 1,750 pounds. If dual straps are used for retaining the upper torso, the total strap loads may not exceed 2,000 pounds.

(7) The compression load measured between the pelvis and the lumbar spine of the ATD may not exceed 1,500 pounds.

(d) An alternate approach that achieves an equivalent, or greater, level of occupant protection to that required by this section may be used if substantiated on a rational basis.

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4 A Review of Research and Development in Crashworthiness of General Aviation Aircraft: Seats, Restraints and Floor Structures

AUTHOR(S)/AUTEUR(S)

5 P. Huculak

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6 Aeronautical Note

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NOTES

13

DESCRIPTORS (KEY WORDS)/MOTS-CLÉS

14 Crashworthiness, seats, restraints, floor structures

SUMMARY/SOMMAIRE

A literature search has been conducted to determine the status of knowledge of the crashworthiness aspects of general aviation aircraft. Research and development work relating to seats, restraints, and floor structures of general aviation aircraft has been selexcted for review.

The primary goal of crashworthiness studies has been the reduction of fatal and serious accidents. Study of the work on seats, restraints and floor structures has revealed that more attention to several research topics could ameliorate high accident rates in general aviation.

15